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Maximum Utilization of Water Resources in a Planned Community

Executive Summary

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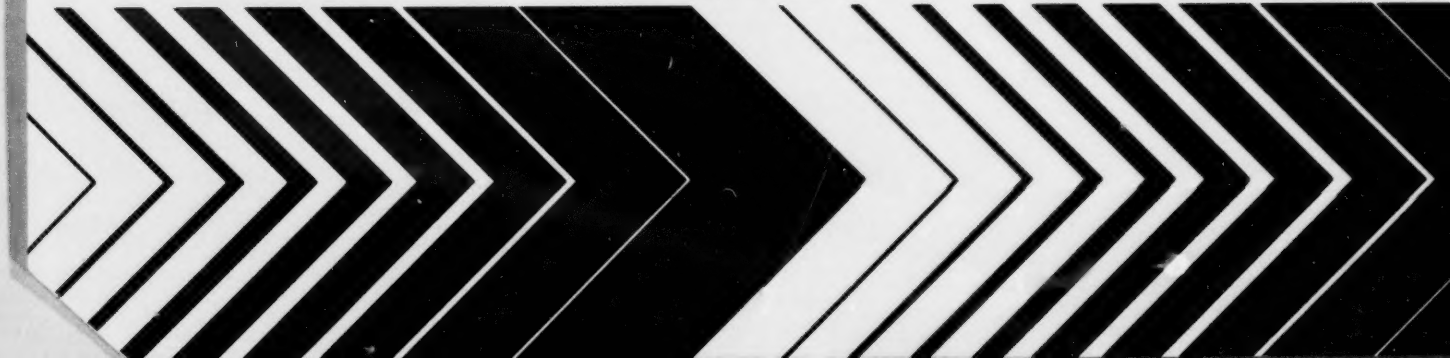

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16. ABSTRACT

Stormwater from four watersheds in the Houston area was monitored over a three year period. Land use in the watershed included undeveloped forest, developing forest, fully-developed residential and mixed commercial-residential.

Chemical parameters monitored included suspended solids, oxygen demand, organic carbon, nitrogen, phosphorous, dissolved oxygen, pH, specific conductance and chlorinated hydrocarbons. Indicator and pathogenic bacterial species were enumerated as well as aquatic and edaphic algae species. Disinfectant demand and algal bioassays were also conducted.

Relationships have been developed between stormwater runoff quality, quantity and land use in an effort to predict pollutant loads. The appearance of a "first flush" is dependent on the parameter measured and watershed characteristics. Rainwater quality contributes significantly to stormwater pollutant loads, especially in urbanized areas. Modifying effects of natural biological processes on nitrogen content in the runoff and effects of the hydrological regime on nutrient limitations were observed. The effectiveness of storage lakes, very positive in the case of suspended solids, were also observed

The Storm Water Management Model (SWMM) was modified to describe the processes occurring in the watersheds and allowed for (1) separate sewer systems, (2) effects of urbanization on base flows, (3) performance efficiency and cost effectiveness of natural drainage systems, (4) four additional water quality parameters (COD, Kjeldahl nitrogen, ~~nitrates, phosphates), (5) hydrologic effects of porous pavement areas.~~

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MAXIMUM UTILIZATION OF WATER RESOURCES IN A PLANNED COMMUNITY

Executive Summary

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components requires a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This project focuses on methods maximizing the use of water resources in a planned urban environment, while minimizing their degradation. Particular attention is being directed towards determining the biological, chemical, hydrological and physical characteristics of stormwater runoff and its corresponding role in the urban water cycle.

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ABSTRACT

An ecologically planned community (The Woodlands, Texas) has adopted a unique water management plan designed to avoid adverse water quality and hydrologic effects due to urbanization while benefiting from the existing natural drainage. The water quantity and quality were monitored by a comprehensive sampling and analytical program to evaluate the physical, chemical and biological effects of its implementation.

Chemical parameters monitored include oxygen demand, organic carbon, nitrogenous compounds, phosphate compounds, dissolved oxygen, pH, specific conductance and pesticides. Numerous indicator bacterial organisms and pathogenic bacteria were enumerated as were various aquatic and edaphic algal species. Disinfectant demand and algal bioassays were also conducted on stormwater runoff.

Relationships were developed between stormwater runoff quality, land use and runoff quantities in an effort to predict pollutant loads. The load-runoff relationships were utilized in a modified version of the EPA Stormwater Management Model (SWMM) to simulate stormwater runoff quantity and quality for watersheds using the "natural drainage" concepts at The Woodlands.

This report was submitted in fulfillment of Grant No. 802433 between the U.S. Environmental Protection Agency and Rice University, Department of Environmental Science and Engineering. This report covers the period July 16, 1973, to May 31, 1976, and work was completed as of December 31, 1976.

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LIST OF ABBREVIATIONS

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DDE	2,2-bis-(p-chlorophenyl)-1,1-dichloro ethylene
DO	Dissolved Oxygen
FC	Fecal Coliforms
FS	Fecal Streptococci
g	mass flow rate
HB	Hunting Bayou watershed
LC_{50}	Concentration of toxicant that is lethal to exactly 50% of the test organism during continuous exposure for a specified period of time.
ortho P	Orthophosphate
P	mass of pollutant
PCB	polychlorinated biphenyls
PDS	slope of the load-runoff curve at some point in time
PS	*Pseudomonas aeruginosa*
PVC	Polyvinyl Chloride
Q	volumetric flow rate
r	rate of runoff
S	total storage
SA	*Salmonella sp*.
SOC	Soluble Organic Carbon
ST	*Staphylococcus sp*.
SWMM	EPA Stormwater Management Model
TC	Total Coliforms
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphate
TSS	Total Suspended Solids
t_p	time to peak flow in a hydrograph
WB	Westbury watershed

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SECTION 1

INTRODUCTION

Non-point source pollution has become of greater concern due to increasingly stringent point source effluent standards and rapid development of urban areas. Urban stormwater runoff is one of the major non-point pollution sources and innovative methods must be developed to minimize the impact of stormwater runoff on receiving waters. One such imaginative water resource plan has been developed for The Woodlands, a planned community in southeast Texas. The U.S. Environmental Protection Agency, Woodlands Development Corporation and Rice University have completed a three year research/demonstration project to evaluate the water resource system at The Woodlands and develop strategies for maximizing the benefits to the community while minimizing the effect on receiving waters.

The hydrological characteristics of a natural watershed change with urbanization. Replacement of flow-retarding vegetation with impervious surfaces, such as roads and buildings, increases the rate and amount of stormwater runoff. Removal of the water is traditionally implemented by the use of an urban drainage system consisting of storm sewers and/or deep, concrete-lined drainage ditches, designed specifically for rapid drainage. Increased runoff volumes and peak flow rates result, creating problems of downstream flooding and channel erosion.

Infiltration of stormwater is a major groundwater recharge source, however emphasis on surface removal minimizes the infiltration rate, resulting in a lowered water table and possible urban land subsidence problems. Water quality deteriorates because natural purification provided by infiltration is compromised.

The urban environment, typified by high population density, provides a major pollutant source for runoff waters (1). Recent investigations recognize the significance and magnitude of pollution problems from urban stormwater runoff. In terms of specific pollutants, the sediment yield problem is the most dramatic. Due primarily to urban construction, urban sediment loads were found to be as much as 75 times greater than loads in agricultural regions (2, 3). Other runoff pollutants reported higher in urban regions include dissolved solids (4), coliforms (5), biochemical oxygen demand and chemical oxygen demand (BOD and COD), polychlorinated biphenyls, heavy metals, pesticides and fertilizers (6-9). An increase in bacterial content is also reported. Claudon (10) stated that agricultural and urban runoff regularly contribute Salmonella sp. to recreational waters. High fecal coliform and fecal streptococcus numbers have been found in urban runoff (11). Snowmelt and related agricultural runoff in far northern climes in the continental U.S. have been shown to contribute high densities of indicator bacteria and pathogens to runoff (12, 13).

The addition of large quantities of inorganic nutrients, particularly nitrogen and phosphorous, to freshwater lakes poses a serious problem in lake management. Municipal sewage (14, 15, 16), agricultural drainage (17), managed forestland drainage (18) and fertilization often accelerate the natural process of eutrophication, thus enhancing the growth of bacteria, algae and aquatic vascular plants. Population densities of these organisms often reach nuisance proportions and interfere with the aesthetic qualities and recreational values of lakes. These "blooms" may discolor, impart unsatisfactory tastes (19, 20) and excrete toxins into the water (21, 22, 23). They can also clog treatment plant filters (24), and, upon decomposition, produce foul odors (14). Late summer "blooms" can create anoxic conditions and cause the death of fish. Accordingly, value of lake properties may depreciate and there may be increased burdens on municipal water systems due to added costs of filtration and deodorization of the water.

Although literature on eutrophication is extensive (25-29), most limnological studies were conducted on lakes that were either eutrophic, or non-eutrophic at the time of study, and few studies were continued long enough to follow changes in the trophic status of lakes. Even fewer studies have been initiated on a drainage system before the construction of lakes. Thus, complete developmental histories of the water resources of particular areas are lacking. Also, it is evident that information on more effective methods of removing mineral nutrients from effluents prior to release into natural waters is badly needed (30).

OBJECTIVES

The overall goal of this research project was to evaluate the water resource plan for The Woodlands and to make recommendations as necessary to maximize its effective utilization through alterations in design or management.

One of the major objectives was to modify and expand the capabilities of the EPA Storm Water Management Model (SWMM) to apply to the "natural drainage" system designed for The Woodlands. SWMM has been expanded to include the following additional water quality parameters: total COD, total Kjeldahl nitrogen (TKN), nitrates and phosphates. The model has been used to evaluate the effectiveness of the "natural drainage" system in minimizing changes in storm runoff quantity and quality and to assist engineers and planners in designing the drainage system for future development phases at The Woodlands.

Since urban areas are typified by a variety of land uses, including residential, commercial and industrial as the broadest categories, determining effects of land use on stormwater quality was conceived as another major project objective. The Woodlands development plan could not provide sufficiently diverse study areas during the project period. Consequently, urban watersheds of similar physiographic and drainage characteristics in Houston were studied to further relate storm runoff water quality to urban land use.

In order to accomplish these two primary objectives, a massive sampling and monitoring program was established. Rainfall, streamflow and over twenty-five water quality parameters were monitored on a regular basis. Included in the water quality program were intensive programs concentrating on bacteriological water quality, chlorinated hydrocarbons and phytoplankton identification and enumeration.

The sampling program included bacteriological tests to evaluate the traditional relationship between indicator organisms (e.g. fecal coliform, fecal streptococcus) and pathogens in stormwater runoff. Disinfection experiments were conducted to determine relative effectiveness of Cl_2, Br_2 and O_3 in untreated stormwater runoff. Toxicological testing determined maximum tolerable concentrations of disinfectant in the receiving stream for maintenance of fish populations. Algal bioassays were conducted to experimentally determine conditions, including nutrient concentrations, necessary to prevent eutrophication in The Woodlands' lakes.

Finally, the performance of a porous pavement was compared to a conventional pavement with regard to runoff amount and quality, wet skid resistance, hydroplaning and other characteristics related to driveability.

SECTION 2

CONCLUSIONS

Runoff Quality

From January 1975 to April 1976, seventeen storms were monitored at six different watersheds in the Houston metropolitan area. The intensive sampling and analytical effort resulted in the following conclusions:

1. Stormwater runoff from an undeveloped, forested watershed is relatively low in pollutants and pollutant indicators. Typical values are: total phosphorous (TP) 0.06 mg/l, total Kjeldahl nitrogen (TKN) 1.24 mg/l, total suspended solids (TSS) 36 mg/l, total COD 42 mg/l, and dissolved oxygen (DO) 6 mg/l.

2. Development in forested watersheds significantly increases suspended solids and nutrients in runoff. COD and other organic parameters are not affected. Development increases surface water turbidity. Increased nutrient loads from developed areas will create algal and macrophyte growth problems in urban lakes.

3. Urban runoff contains higher nutrient and solids loads than forest runoff. Nutrient concentrations (ammonia, TKN, nitrate, nitrite, TP, ortho phosphates) are as much as 10 times greater in urban areas. TSS concentrations are 4 times greater. Higher concentrations, combined with increased runoff coefficients (the amount of runoff for a given amount of rainfall), provide receiving waters with heavy pollutant loads in urban areas. Sediment buildup and algal growth problems result.

4. A man-made lake serves as an effective trap for excessive sediments transported by construction site runoff. During seven separate storm events totaling 10.2 in. (26 cm) of rainfall, 180 tons (1.6×10^5kg) of sediment entering 110 ac-ft (13.56 ha-m) Lake Harrison was reduced to 34 tons (3.08×10^4 kg) in the effluent. This was an 81% reduction in sediment load.

5. A definite first flush is observed for urban and undevelped watershed runoff, most commonly for TSS and turbidity parameters. The flush is related to transport of streambed sediments. Urban drainage systems have increased transport potential and therefore exhibit higher flush concentrations.

6. Rainwaters contain phosphates, nitrogen and COD which account for a significant portion of runoff pollutant loads.

7. Undisturbed soils are capable of removing nutrients found in rainwater. Disturbed soils in developing areas lose this capability.

8. Municipal wastewater would require advanced treatment to compare with nitrogen and phosphorous concentrations in stormwater runoff. Secondary treatment of wastewater will lower TSS and COD concentrations below that in stormwater runoff.

9. A linear relationship exists between total pollutant loads and total stormwater runoff, which is useful in comparison between watersheds and analytical prediction of stormwater pollutant loads.

10. A statistical ranking of four watersheds, on a lb/ac/in of runoff basis, indicates that urban watersheds are clearly the greatest producers of suspended solids and nutrient loads. Loads from forested and developing watersheds are lower by as much as an order of magnitude.

11. Load-runoff curves may be used to sequentially simulate mass flow curves. Simulation of a six-month period, containing three measured storm events, produced reasonable comparisons of of observed and simulated curves.

Eutrophication Potential

1. Algal associations encountered at The Woodlands were indicative of oligotrophic or slightly mesotrophic waters.

2. Phosphorous is the limiting nutrient for algal growth in the Conference Center Lakes and Panther Branch during low flow, while nitrogen is more limiting in stormwater runoff samples. Consequently, operation of the phosphorous removal process for the treated sewage effluent entering the lakes is not necessary during rainy periods. The savings could amount to $50,000/year.

3. Surface runoff from fertilized soilds serves as a source of nutrients and troublesome algae. Fertilization of the golf course, with subsequent increase in soil pH, results in larger standing crops of blue-green algae and diatoms in the soil.

4. Urban stormwater runoff contains higher bacterial concentrations than runoff from forested areas. Substantial numbers of bacteria, including pathogenic species, were found. Stormwater runoff generally exceeded state recreational standards for fecal coliforms (200 cells/100 ml).

Disinfection

1. Excessive doses of chlorine or ozone are required for effective disinfection of stormwater runoff. Chlorine and ozone demands greater than 8 mg/l and 32 mg/l, respectively, were measured, primarily a result of high TSS concentration.

2. Toxicity studies using channel catfish (*Ictalarus punctalus*) in a flow-through bioassay system have established maximum safe surface water concentrations at 7 μg/l and 3 μg/l for chlorine and ozone, respectively.

Porous Pavement

A porous pavement parking lot was installed at The Woodlands, Texas and its performance compared to a conventional, dense pavement parking lot. The following conclusions resulted from the study:

1. Porous paving may be used effectively to store and release stormwater which would otherwise cause erosion or flash flooding. The quality of the released water is generally better than that of runoff from standard paving.

2. Unacceptable lead concentrations suggest that stored water under porous pavement should be prevented from contacting drinking water supplies.

3. Porous pavement is comparable to conventional paving in terms of driveability and safety. Mud and dirt from construction activities in the vicinity can clog porous paving.

4. Periodic maintenance of the paving should be performed by brush sweepers with vacuum followed by high pressure water washing.

5. A more durable porous pavement can be produced by using lower penetration or stiffer asphalt than that at The Woodlands.

Stormwater Management Model

The SWMM release of February 1975, referred to in this report as the original SWMM version, was extensively modified. The capabilities of the modified version have been expanded to model runoff and water quality from natural drainage areas. The study areas where the new capabilities were tested are The Woodlands and Houston, Texas. During the course of this study the following conclusions were reached:

1. After correction of errors in infiltration rate computation, the modified SWMM predictions of observed peak and total discharge were relatively accurate but the pollutant concentration predictions, which are dependent on exact hydrograph replication, could not be modeled for the study area.

2. Although runoff from natural drainage areas is of better quality than that from areas with conventional storm sewer drainage, the effect of construction activity in both types of areas could not be determined by the original SWMM version. The predicted values were always too low. But, modeling of erosion from construction activities is now possibile by use of the modified SWMM version.

3. Biochemical oxygen demand (BOD) data produced inconsistent results and, therefore, BOD modeling proved unsatisfactory. Data for COD were consistent and were used to model oxygen demand.

4. The functional relationship between pollutant mass and runoff volume can be linearized by the use of logarithmic transfroms. Resultant linear equations can be used to determine loading rates and total pollutant transport from a watershed.

5. The exponential pollutant removal or decay coefficient can be considered as a contstant in all geographical areas. The modified SWMM allows for selection of the value of this coefficient by the user.

6. The modified SWMM can transport flow through natural channels with a minimum of input data requirements. Each natural channel is described by a series of coordinates, and the program now calculates the area-discharge curves which formerly had to be input for each natural channel.

7. The modified SWMM can determine the cost efficiencies in the use of natural drainage systems relative to those for conventional drainage systems using either user supplied or default unit cost estimates.

8. The modified SWMM can provide a detailed analysis of storage and flow into and out of porous (pervious) pavement systems. The drain outflow, surface runoff, and storage volumes can be determined; but the lack of comprehensive data precluded the modeling of water quality in porous pavements.

9. The modeling schemes developed during this study require considerable input data preparation and, consequently, the modified SWMM, when applied to natural drainage systems, is more user dependent.

SECTION 3

RECOMMENDATIONS

Sediment discharge from construction area stormwater runoff should be controlled by sedimentation basins or more sophisticated methods.

Research is needed to establish the relationship of air quality to rainwater and stormwater runoff quality. Special attention should be focused on effects of projected ambient air quality criteria.

More standardized methods should be instituted to describe storm events and watershed characteristics and to reduce data resulting from a stormwater management program.

A water quality management program should be instituted to ensure proper maintenance of the aquatic ecosystems in The Woodlands. The first flush nutrients during storm events should be captured or diverted and treated before release into the Conference Center Lakes. Homeowners and golf course managers should be encouraged to select and apply fertilizers with caution, since excessive, long-term fertilization could result in nutrient buildups in aquatic systems of The Woodlands.

The wet weather ponds and marshes in The Woodlands should be managed since they often overflow into Panther Branch. Excessive concentrations of algae and nutrients in these habitats would ultimately affect the water quality of Panther Branch and its downstream receiving waters, especially if Panther Branch water is utilized to control water levels in preexisting and future lakes.

Nutrient concentrations and detention times in the Conference Center Lakes should be controlled in order to prevent excessive concentrations of algae. Treated sewage effluent and/or well water could be used to periodically flush these lakes and dilute algal nutrients.

The aquatic vascular plants should be managed in order to prevent them from totally encompassing the Conference Center Lakes. This might be accomplished by increasing the slopes of the littoral zones and/or by harvesting and removal of the plants.

Future investigations on water resources for bacterial assessment and management of stormwater runoff should establish baseflow diurnal variability in indicator bacteria concentrations prior to evaluating storm events.

Further investigations should determine the effect of land use on fecal coliform/fecal streptococci ratio.

Alternative methods must be developed to yield greater reliability for bacterial indicator and pathogen quantification.

Settling and dieoff patterns of bacteria in impoundments with relatively short detention times suggest that if disinfection is to be applied to a particular stormwater source, if at all feasible, the equivalent of stilling basins should be employed.

Examination of bacterial data for comparison with other water quality parameters for analysis or resource management purposes should not be accomplished using a simple arithmetic approach because non-linear relationships exist between variables. Bacterial data should be transformed to $\log_{10}$ basis.

Before porous pavements are used for stored water release to aquifers, the fate of lead salts in the percolated water should be determined.

Studies are required for the design of porous pavement parking lots in other than flat areas in order to avoid flooding of low areas in a lot.

The water quality relationships developed in this study should be verified with data from other watersheds across the country to determine the possibility of data transfer. New or revised coefficients may be developed for nonhomogeneous watersheds or different climatological regions. If linearization of the log transforms of water quality data is found to be universally applicable, the prediction of water quality will be facilitated.

The use of the modified SWMM should be promoted so that other users may utilize the vastly improved capabilities and flexibility of the model. The use of baseflow recessions in designing for low frequency or dry weather flows should be considered. Porous pavements should be evaluated, by means of the modified SWMM, as urban runoff control facilities. The reduction of data requirements for modeling natural streams should be emphasized and the use of the modified SWMM in modeling natural drainage systems should be encouraged.

Water quantity and quality sampling at The Woodlands should be continued at least until the watersheds have stablilized and erosion rates are reduced to pre-development or uniform levels.

Records of all construction activity should be maintained so that the location and total area under construction during a storm event will be known. This record will prove very helpful in modeling water quality from that watershed.

The modeling or erosion in the SWMM needs to be refined. The coefficients of the Universal Soil Loss Equation were derived for agricultural areas and their applicability to urban and forested areas is limited. Possibly, a new approach may have to be considered. The significance of pollution from construction activity has generally been underestimated.

SECTION 4

SITE DESCRIPTIONS

Several sites in the Houston Metropolitan Area were chosen to determine if stormwater runoff quality is dependent on land use and development activities. The primary study site is The Woodlands, Texas, a planned satellite city selected for a comprehensive investigation of runoff quality during all phases of development. Two other watersheds were chosen to supplement data collected from The Woodlands. Hunting Bayou is a developed watershed with strong industrial influences and deteriorating residential areas. Westbury Square is a middle class residential area chosen because of the absence of construction in the watershed. The locations of these study sites are shown in Figure 1. Each watershed is comprehensively described in the following text.

THE WOODLANDS

General Description

The Woodlands is a planned community being developed in southern Montgomery County, Texas. The community is situated in a heavily forested tract about 35 miles (56 km) north of Houston, directly west of Interstate 45 (see Figure 1). The Woodlands encompasses 17,776 acres (7194 ha) and will be developed over a twenty-year period beginning September, 1972. In contrast to a residential subdivision, The Woodlands will contain all services of a modern city, including facilities for social, recreational, educational, commercial, institutional, business and industrial pursuits. The community concept is committed to high standards for environmental and lifestyle quality. The phased, long range development places priority on ecological preservation and balance, as well as social and habitational quality. This objective is to be accomplished through a comprehensive environmental preservation and management program, including planning and design controls. The water resource system in The Woodlands, including its drainage system, is a good example of such planning and was the primary subject of this research.

Development Plan

The prime objective of The Woodlands is to provide the finest urban environment in the Houston metropolitan area in

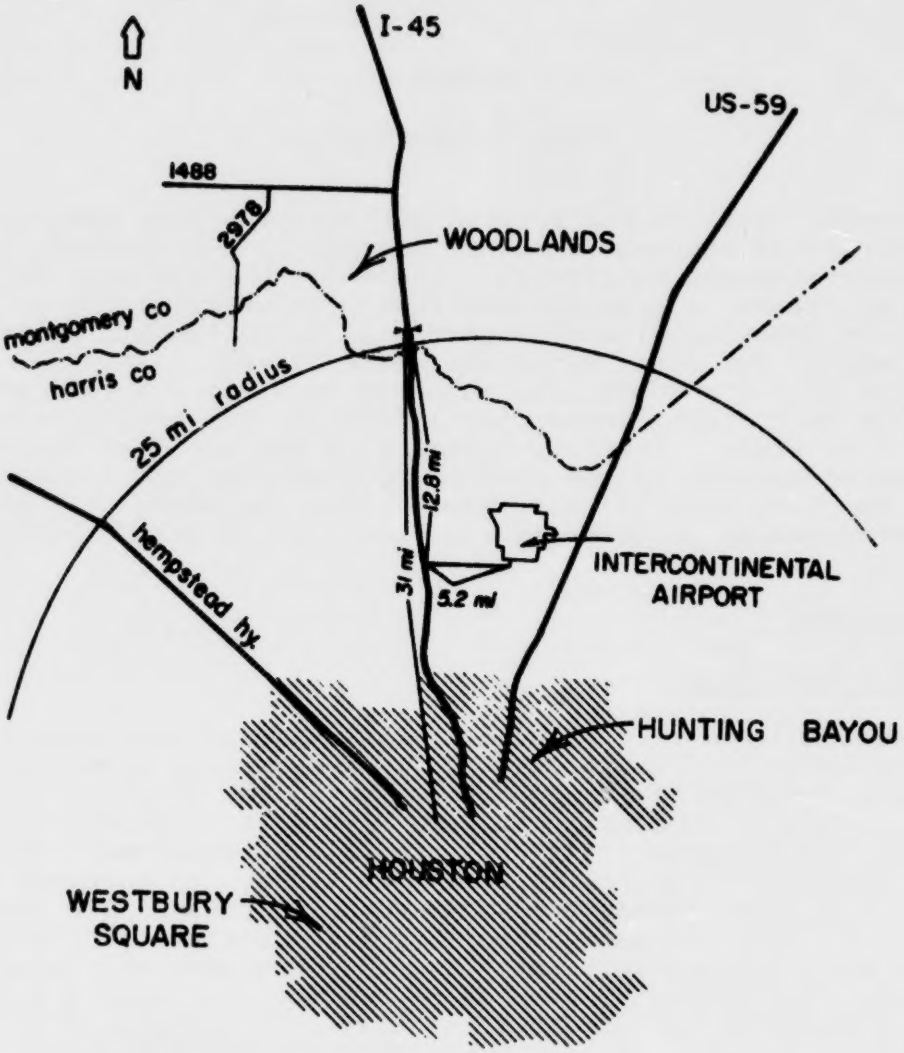

N
I-45
US-59
1488
2978
WOODLANDS
montgomery co
harris co
25 mi radius
12.8 mi
31 mi
5.2 mi
INTERCONTINENTAL AIRPORT
hempstead hy.
HUNTING BAYOU
HOUSTON
WESTBURY SQUARE

Figure 1. Location of study sites.
(1 mi = 1.6 km)

terms of physical setting and quality of human life and community services. The basis for all aspects of development in The Woodlands is a unique ecological inventory conducted from 1971-1973. The geology, soils, drainage, water resources, weather, vegetation, and wildlife endemic to The Woodlands were critically evaluated for determining the most desirable location of roads, streets, homes, offices, and other physical structures.

Land use allocation for The Woodlands provides for undeveloped areas. Residential areas will occupy 6,820 acres (2760 ha) of The Woodlands site, while 1,699 acres (688 ha) are designated for restricted industrial use. Additional area has been allocated for retail, commerical, office, open space, and other land sales. Approximately one-third (30.2%) of The Woodlands has been designated as open space. The majority of the open space will be located within the floodplain of Panther Branch and its major tributary, Bear Branch.

Climate

The macroclimate of the Houston metropolitan area is dominated by the Gulf of Mexico. Winters in the region are normally mild, while summers are hot and humid. The daily winter temperature is about 50°F (10°C), whereas the mean daily summer temperature is 82°F (27.8°C).

Average yearly rainfall in The Woodlands totals about 46 in. (117 cm) and is evenly distributed throughout the year. April, May, November and December are usually the wettest months, while March is the driest month. The quantity variation of rainfall for specific storm events can be significant especially during summer months. Most rainfall occurring during June, July, August, and September is associated with thunderstorms. Precipitation during these months is unpredictable and erratic. Frequenty an inch or more (a few centimeters or more) of rainfall can be recorded in one part of a watershed, while a very short distance away no precipitation occurs.

Plant Ecology and Wildlife

The tract of land upon which The Woodlands will be constructed is comprised, almost completely, of forest. Eight major forest ecosystems exist within the development. Some of these ecosystems, including wet weather ponds, marshes, and grasslands, are extremely unique and differentiated. The trees which are indigenous to the site include red oak, pine, sweetgum, hickory, yaupon, water oak, post oak, and winged elm.

Because of the diversity of vegetation and varied food sources, most of the fauna endemic to southern watersheds are found on the site. Common birds include blue jays, red-headed woodpeckers, cardinals, Carolina chickadees, Carolina wrens and pink warblers. Mammals frequently encountered are whitetail deer, raccoon, armadillo and ringtail cat. Numerous snakes and other reptiles are also frequently observed on the site. The environmental impact of the development upon the wildlie and vegetation has been estimated to be minimum (31-33).

Soils

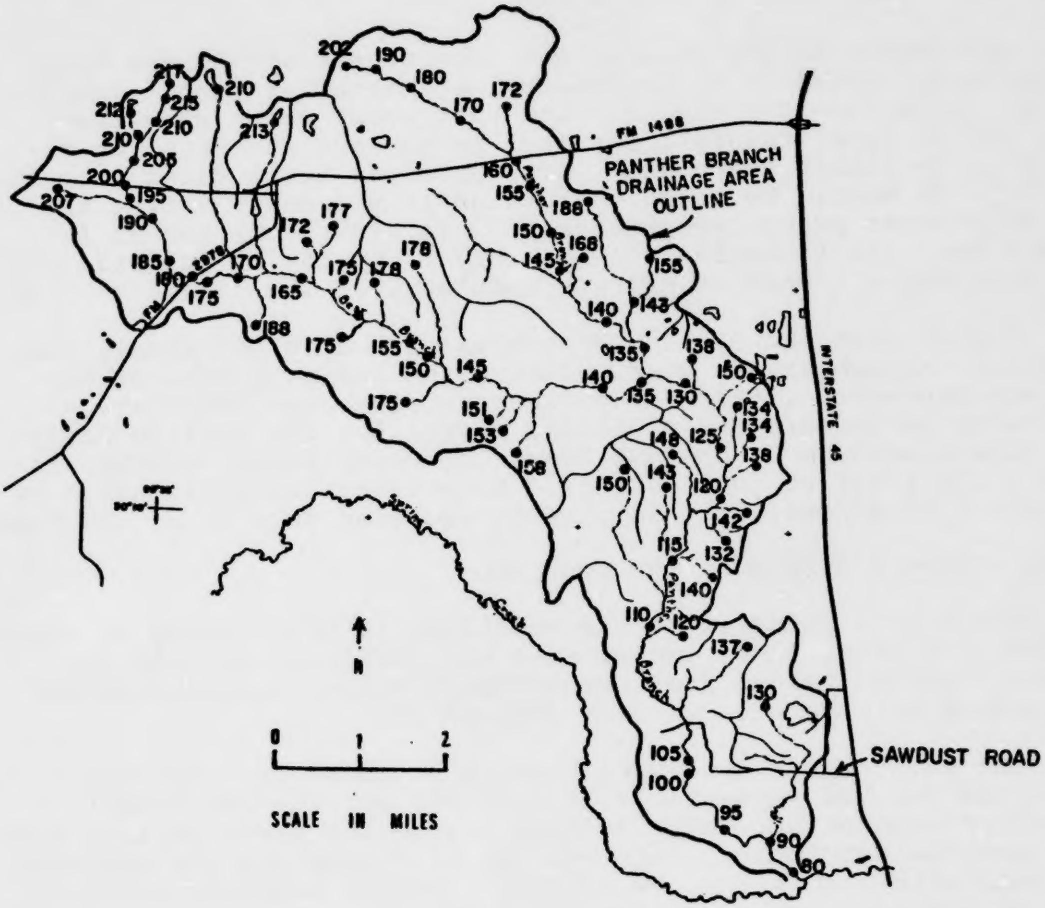
A comprehensive soil survey was performed at The Woodlands development site by the USDA Soil Conservation Service, from March 1972 to June 1973. The results of this survey are published in a report entitled "Soil Survey of The Woodlands" (34). The survey describes a total of 22 soil types in the area.

The soils on The Woodlands site characteristically contain a zone of clay accumulation. The clay zone, which generally occurs at a depth of from 18 in. (46 cm) to 6 ft (1.83 m) below the ground surface, is relatively impermeable and creates a seasonal perched water table. The high water table is an important factor in maintaining the diverse vegetaion which occurs on the site. Of major concern in the impact that development could have in reducing recharge to this shallow reservoir due to soil compaction and construction of impervious surfaces. If recharge is significantly decreased, it could have a detrimental effect on the more sensitive plant species on the site. Also, a reduced recharge could have a significant effect on the base flow characteristics of the streams draining The Woodlands site.

Existing Drainage

The natural drainage for The Woodlands community is shown in Figure 2. Approximately 80% of the development is drained by Panther Branch, a tributary of Spring Creek. The remaining portion of the development drains directly into Spring Creek, which has a total drainage area of 750 sq mi (1942.5 sq km). Because Panther Branch and its major tributary, Bear Branch, represent the major existing drainage for the development site, the hydrologic, morphologic and transport characteristics of this stream are of extreme importance.

Both Bear Branch and Panther Branch meander extensively along well-defined, and low-flow channels, respectively, 9.0 (14.48 km) and 14.6 mi (23.5 km) in length. Alluvial sediments, small riffles, and slow moving pools are commonplace within Panther Branch and Bear Branch. The width of the low-flow channel is highly variable but is normally between 5 and 20 ft (1.5 and 6.1 m). When the capacity of the defined channel is exceeded, storm runoff discharges into a very broad, flat flood plain, presently covered with heavy brush. Flood runoff is characterized by low velocities and shallow depth because (a) a large land area is inundated, (b) flow resistance is high, and (c) hydraulic slope is low. Excluding those areas presently under construction, essentially no evidence of any serious erosion can be found anywhere in Panther Branch watershed.


202
190
180
172
170
FM 1488
PANTHER BRANCH DRAINAGE AREA OUTLINE
217
215
212
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207
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185
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FM 2978
175
170
172
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138
143
150
120
142
115
132
140
151
153
158
110
120
137
130
105
100
95
90
80
INTERSTATE 45
SAWDUST ROAD
N
0
1
2
SCALE IN MILES

Figure 2. Existing drainage network for The Woodlands (numbers shown indicate elevation above mean sea level).

1 mi = 1.6 km

Flow rate measurements in Panther Branch indicate that water velocities as low as 0.04 to 0.10 ft/sec (.012 to .03 m/s) are typical for low-flow conditions. The slow travel rate is a result of low channel slopes present throughout the drainage network. The total change in channel elevation across the drainage basin is about 120 ft (36.5m m), with an average rate of change of 5 to 7 ft/mi (.95 to 1.33 m/km).

The impact of low channel and land slopes within The Woodlands is reflected in an extremely low stormwater runoff coefficient. USGS data for the 1973 and 1974 water years show that only 23% of total rainfall resulted in surface runoff. The remaining 77% either evaporated, transpired or infiltrated into the ground. It should be noted that rainfall was heavy during the 1973 and 1974 water years, respectively 77 in. (195.6 cm) and 51 in. (129.5 cm). It is estimated that only 10 to 15% of rainfall will run off during a year of average rainfall, 45 in. (114.3 cm) (35).

Runoff from the Panther Branch watershed is not evenly distributed throughout the year. During the summer months of May through September little discharge occurs, except immediately following an intense and prolonged rainfall. The average daily low flow discharge at Sawdust Road, including summer months, is 1 to 2 cfs (.028 to .056 m^3/sec). An average daily discharge of 100 cfs (2.8 m^3/sec) at this site is exceeded only 5% of the time.

WATER RESOURCE SYSTEM OF THE WOODLANDS

The annual rainfall at The Woodlands is partitioned as runoff into existing lakes and streams and infiltration into the ground. Losses result from evapotranspiration, evaporation and subsurface transport to streams (Figure 3).

The maintenance of a satisfactory groundwater reservoir above the perched water table is critical for the continued growth of vegetation. Any drainage system for The Woodlands must consider the detrimental consequences of disrupting the movement of water within this shallow aquifer. Deeper aquifers (1800 ft) (549 m) are used for community water supply.

A series of wet weather ponds and variable volume lakes will serve as recreational centers, wildlife preserves and, more importantaly, storage for stormwater runoff. This system of water reservoirs contributes to the maintenance of an adequate perched water table for plant life. Lake water will be lost primarily through surface evaporation and irrigation. Inflow to the lake system will result primarily from stormwater runoff and reclaimed water water from 2 or 3 sewage treatment plants. The projected volume of waste water is 20 mgd (0.88 m^3/sec). If necessary, treated sewage effluents can be discharged directly into Panther Branch.

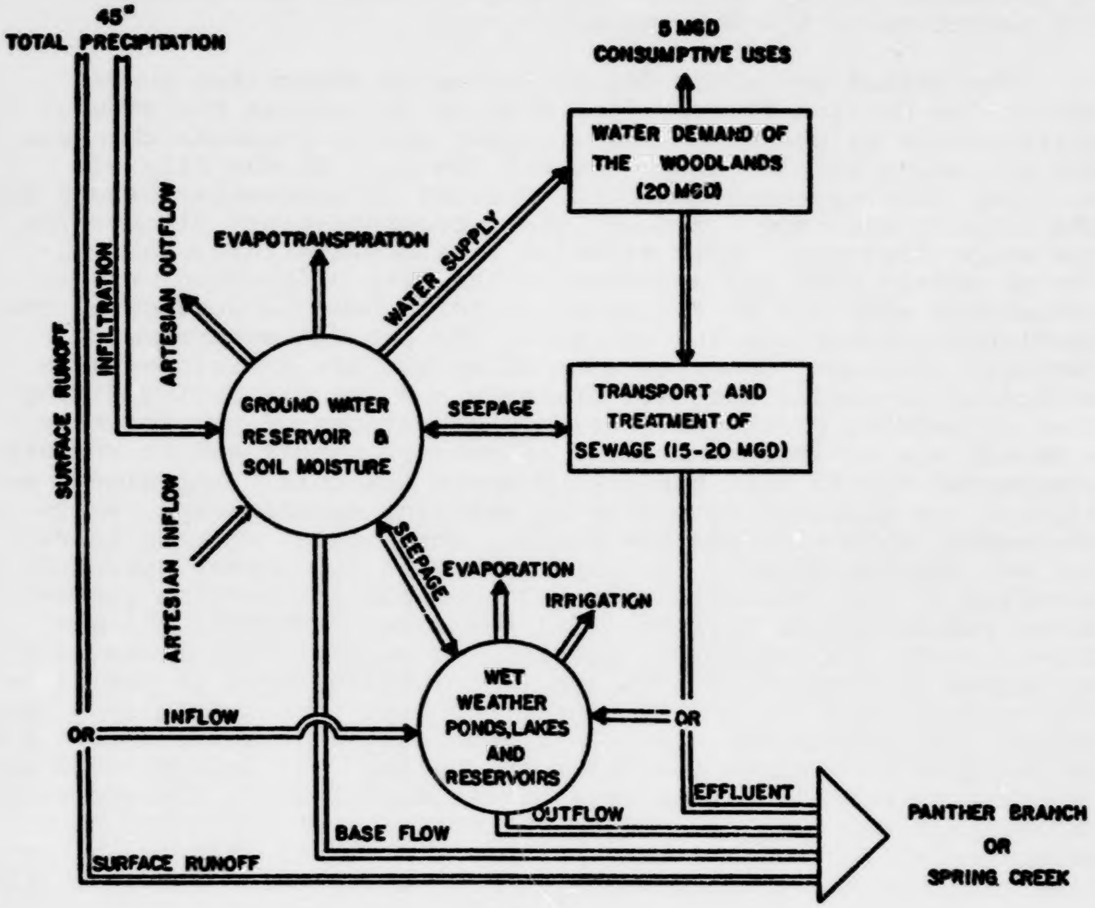

45"
TOTAL PRECIPITATION
5 MGD
CONSUMPTIVE USES
WATER DEMAND OF THE WOODLANDS (20 MGD)
EVAPOTRANSPIRATION
WATER SUPPLY
ARTESIAN OUTFLOW
INFILTRATION
SURFACE RUNOFF
GROUND WATER RESERVOIR & SOIL MOISTURE
SEEPAGE
TRANSPORT AND TREATMENT OF SEWAGE (15-20 MGD)
ARTESIAN INFLOW
SEEPAGE
EVAPORATION
IRRIGATION
WET WEATHER PONDS, LAKES AND RESERVOIRS
OR
INFLOW
OR
EFFLUENT
OUTFLOW
BASE FLOW
SURFACE RUNOFF
PANTHER BRANCH OR SPRING CREEK

Figure 3. Schematic water balance for The Woodlands.

"Natural Drainage System"

The Woodlands Development Corporation has specified that the basic drainage system for their new community will utilize "natural drainage" concepts. These design principles have been reported in "Natural Drainage Systems: An Alternative to Conventional Drainage Systems" by Winslow, Veltman and Espey (36) and will not be described in detail herein. Rather, a brief summary is presented on the "natural drainage" concept and reasons for its selection in The Woodlands.

The normal procedure for disposing of stormwater runoff within the Houston Metropolitan Area is to enlarge the natural drainageways by deepening and widening existing stream channels and providing supplementary lateral drains. In the City of Houston, this approach generally results in stormwater sewers for the lateral drainage and deep, wide, concrete-lined ditches for the major drainage. This solution to stormwater disposal, although widely used and approved by the City of Houston, was incompatible with one of the major criteria used in developing The Woodlands--preserving and enhancing the natural environment. "Natural drainage" concepts adopted by WDC are envisioned as a method of providing adequate drainage and yet minimizing disruption of natural processes. Primary objectives of the drainage approach are to impede movement of surface runoff and to recharge stormwater runoff into the ground where feasible. Impediment and storage are provided by modifying existing drainageways, where necessary, with wide shallow swales, check dams, storage lakes and wet weather ponds. In comparison with the normal approach, benefits of the "natural drainage" approach in managing stormwater runoff are as follows: (a) maximizes recharge, (b) minimizes runoff, (c) minimizes erosion and siltation problems, (d) minimizes vegetation removal, and (e) minimizes cost of the drainage system. The "natural drainage" concept is essentially a recharge and containment approach to managing stormwater runoff and is designed to achieve the following goals: (a) reduce legal entanglements resulting from excessive runoff leaving the property, (b) sustain existing plant life by retention of a stable, high water table, (c) sustain planned perennial lakes, and (d) minimize clearing and grading costs for swale and storm sewer trenching.

CLC LAKE SYSTEM

The man-made lake system at The Woodlands Commercial, Leisure and Conference Center (CLC) was filled during March 1974. The system, known as Harrison Lake, is comprised of 2 lakes separated by a decorative waterfall. To implement a continuous flow over the connecting waterfall, the upstream, smaller lake, designated Lake B, is constant volume. In dry weather there is no streamflow into the lakes and the water level of Lake B is maintained by recirculating water from the lower lake, Lake A, or by the inflow of tertiary treated sewage. Sewage flow from The Woodlands community is not yet a major source of lake water, however, projected sewage flow is 6 mgd (.26 m^3/sec). During wet weather, Lake B is designed to receive stormwater runoff and serve as a sedimentation basin for the 337 acre (136.4 ha) watershed under construction at this time. Upon completion it will include an 18 hole golf course meandering through a residential area.

Lake A is a variable volume lake to be used for non-contact recreation. Lake discharge is controlled by an outlet box at an elevation of 121.8 ft (37.1 m) above sea level. Water from Lake A irrigates The Woodlands Gold Course bordering the lake's eastern and northern shores. In dry weather, the water level drops due to evaporation and groundwater is pumped into the lake to compensate. Lake water is not lost to groundwater recharge due to a clay bottom which serves as an effective seal.

Porous Pavement

An experimental porous pavement parking lot has been constructed at The Woodlands as a possible solution to the problem of excess runoff from impervious urban surfaces. The lot consists of a permeable asphalt-concrete topping, overlaying a coarse base and fill material. The pavement is designed to allow rainwater to percolate through the asphalt and infiltrate into an existing groundwater reservoir. Besides reducing urban stormwater runoff volumes, porous pavement has other benefits such as anti-skid properties and better visibility of road markings.

HUNTING BAYOU WATERSHED

The Hunting Bayou watershed is located in northeast Houston near the intersection of Highways 50 and 610. The 1,976 acre (800 ha) watershed is characterized by low land slopes and impermeable soils with high clay content. Primary drainage channels are trapezoidal in shape and lined with vegetation which varies in density from moderate to very heavy depending upon the season and maintenance schedules. The majority of the secondary drainage is provided by roadside, grass-lined swales comparable to the drainage design at The Woodlands. A fourth of the area is drained by storm sewers. There are no known effluents entering the drainage system, however, point sources are probable due to the age of the residential districts (illicit sanitary sewer connections to the storm system and the presence of industrial influences). The area is poorly maintained and stream channels are sometimes used as dumping areas for waste materials such as oil and grease, old tires, and other refuse.

Land use in the watershed is mixed (Figure 4) with residential areas comprising the largest segment. Residences are mostly single family dwellings of low value. Table 1 gives demographic information regarding the indigent population.

Industrial activity in the watershed includes meat packing and rendering plants, wrecking yards and mechanical contractors. Various commercial establishments in the watershed support the residential population. Construction in the watershed is centered around completion of Interstate Highway 610.

WESTBURY SQUARE WATERSHED

The "natural drainage" system utilized by The Woodlands is an innovative method for controlling stormwater runoff and preventing water quality deterioration. A Houston watershed with a conventional drainage system was selected as a comparative study site. The residential land use of Westbury is similar to that being constructed at The Woodlands.

The 210 acre (85 ha) watershed is located in Southwest Houston and is comprised exclusively of single-family residential dwellings. No commercial or industrial influences are present in this area. The watershed is completely developed and contains no construction sites, empty lots, and no undeveloped land. Figure 5 and Table 2 provide watershed information.

Demographic information from the 1970 census presents the area as upper-middle class, median annual income of $19,000. Population density is approximately 11 persons/acre (27 persons/ha), or 4 persons/household.

The separate stormwater drainage system consists of lateral drainage provided by concrete pipe, 18 in. to 54 in. (45.72 cm to 137.16 cm) diameter, connecting with a main collecting channel at roadway intersections. The channel is a 10 ft (3 m) deep open grass-lined ditch, often choked with vegetation in the summer months. The ditch passes through culverts beneath roadways, and at these points, ponding occurs upstream and downstream providing slight storage of runoff and a reduction of flow velocity. Low runoff coefficients can be expected due to the low land slope of only 0.8%. Impervious cover is estimated at 35.4%. No dry weather flow is present in this watershed.

Soils in the area are predominately dark clays and loams, characterized by low permeability and high available water capacity. The soils tend to be mildly alkaline or neutral. Rainfall in the area averages 39.5 in/yr (1.0 m/yr).

TABLE 1. HUNTING BAYOU WATERSHED CHARACTERISTICS

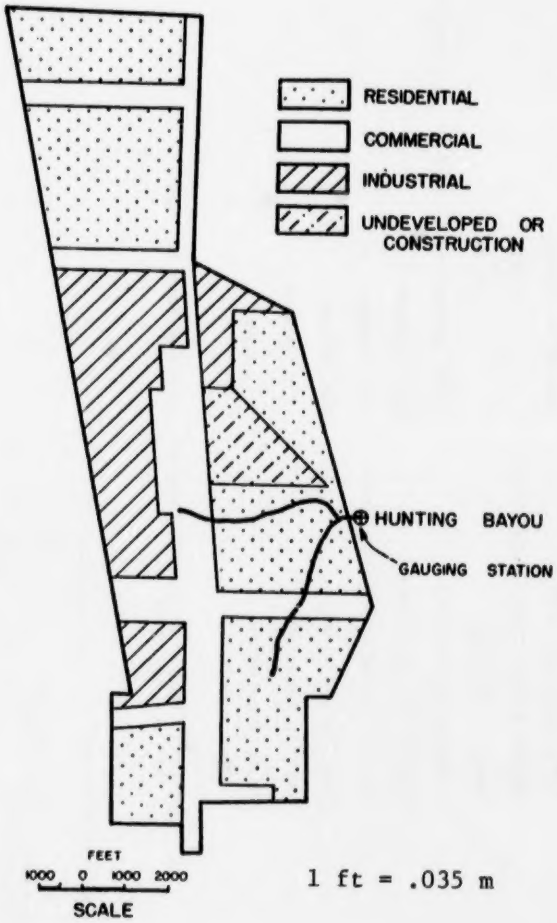
Total Drainage Area	1,976 acres (3.08 mi^2)	
Residential - (Mostly single family low income)	948 acres	48%
Commercial -	629 acres	32%
Industrial - (Meat packing plants, contractor's yards, scrap yards, chemical and building firms)	276 acres	14%
Undeveloped or under Construction - (Construction includes 610 Loop Interchange)	123 acres	6%
Impervious Cover	21%	
*Population Density	7,915 persons/$mile^2$	
Family Mean Income	$6,070.00	
Family Median Income	$5,549.00	
Median School Years Completed	9.4 years	
Home Values - Mean	$8,700.00	
Persons/Household	3.46 persons	
Rooms/Housing Unit	4.3 Rooms	

* Data Derived from 1970 Census: Census tracts 205, 206, 207 are averaged.

1 ac = .405 ha

1 ft = .305 m

1 mi^2 = 2.59 km^2


RESIDENTIAL
COMMERCIAL
INDUSTRIAL
UNDEVELOPED OR CONSTRUCTION
HUNTING BAYOU
GAUGING STATION
FEET
1000 0 1000 2000
SCALE

1 ft = .035 m

Figure 4. Hunting Bayou watershed land use.

TABLE 2. WESTBURY SQUARE WATERSHED CHARACTERISTICS

Total Drainage Area	210 acres (518ha)
Single Family Residential Areas	100%
Impervious Cover	35.4%
*Population Density	7,040 persons/mile^2 (2718 pers/km^2)
Family Median Income	$19,000/year
Median School Years Completed	14.7 years
Home Values - Mean	$29,000.00
Persons/Household	3.8 persons
Rooms/Housing Unit	7.5 Rooms

* Data derived from 1970 Census: Census tracts 427 and 428 are averaged.

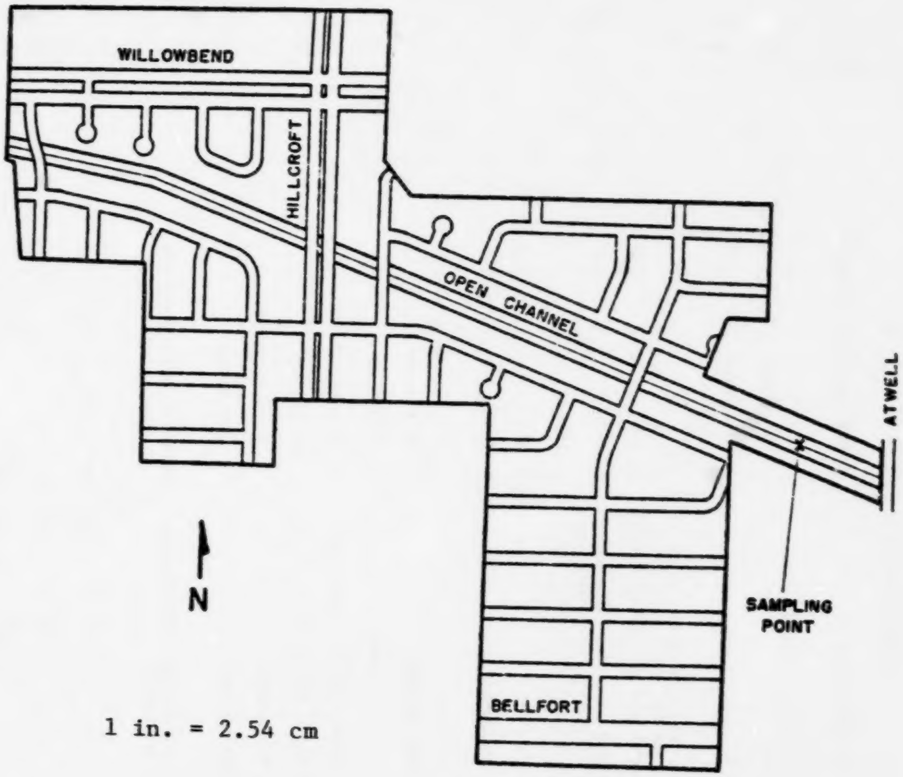

WILLOWBEND
HILLCROFT
OPEN CHANNEL
ATWELL
SAMPLING POINT
N
BELLFORT
1 in. = 2.54 cm

Figure 5. Westbury Square watershed (scale 1 in. = 1000 ft).

SECTION 5

SAMPLING AND MONITORING PROGRAMS

This section summarizes the field sampling and monitoring programs initiated in September 1973. The sampling programs were divided into two distinct segments. First, selected terrestrial and aquatic environments within The Woodlands were sampled during periods of no overland runoff (low-flow conditions) for the occurrence and concentration of selected physical, chemical and biological constituents. These measurements comprise a low-flow data bank from which (a) the effect of urbanization on the water resources of The Woodlands can be quantified, and (b) the water quality criteria of the lakes within The Woodlands can be established to insure their usage for recreational and aesthetic purposes. Sampling points were located for the comparison of undeveloped and developing areas within The Woodlands. Sampling sites downstream in the drainage area of Panther Branch provide data to establish the impact of The Woodlands development upon the water quality of the receiving body (Spring Creek).

The second phase of the sampling program concerned itself with quantifying the chemical, physical, hydrological and biological characteristics of overland runoff and its subsequent impact on the water resources of The Woodlands. The stormwater sampling program involved the development of pollutographs for at least 25 different water quality parameters per storm event. Not every storm event was evaluated but, rather, selected storms were monitored to define various hydrologic and seasonal conditions.

A comprehensive hydrologic network was established within the study area, focused around continuous discharge recording stations operated and maintained by the Water Resources Division, U. S. Geological Survey, Houston, Texas at the request of The Woodlands Development Corporation. The purpose of this network was to accurately delineate the movement of water, especially surface flows, within the new community. For this purpose, a weather station, rain gauges, streamflow stations and groundwater observation wells were established.

DRY WEATHER PROGRAM

Dry weather field sampling programs were conducted within the Panther Branch watershed, in the immediate vicinity of The Woodlands development. These programs were directed toward gathering a basic data bank on the algal, bacterial, chemical, hydrological and physical characteristics of this area's surface water resources. Water, soil, plant and animal samples were collected on a regular basis for analysis.

The locations of aquatic sampling sites are shown in Figure 6. Stream water samples were collected at sites located from the headwaters of Bear Branch and Panther Branch downstream to Spring Creek. Several ponds and marshes within the watershed were also sampled. Sampling frequency was about once per month.

Specific analysis performed on water samples included temperature, dissolved oxygen (DO), pH, turbidity, total suspended solids (TSS), soluble COD, total COD, soluble organic carbon (SOC), total Kjeldahl nitrogen (TKN), total phosphorous (TP), orthophosphate (ortho P), ammonia (NH_3), nitrite (NO_2), nitrate (NO_3), BOD, and specific conductance. The presence of specific pesticides and chlorinated hydrocarbons was also determined. In addition, the following bacterial enumerations were conducted: fecal coliform, fecal streptococcus, total coliform, total bacteria, Salmonella-Shigella sp., Pseudomonas sp., and Staphylococcus sp. Algae and macrophyte enumerations were also conducted.

Other water samples were collected for experimental purposes to determine limiting nutrients for algal growth and bacterial disinfection characteristics.

Soil samples were collected from 21 sites located in the study area and analyzed for bacterial and algal content. Leachates from these samples were tested for pesticides and nutrients.

Plant and animal samples were collected on a regular basis and examined for the presence of pesticides and chlorinated hydrocarbons. Aquatic animals collected include fish, shrimp and crayfish.

STORM EVENT PROGRAM

The stormwater monitoring program used a hydrologic network combined with intensive sampling to characterize runoff quality. Runoff samples were collected at six sites, four located within The Woodlands, a fifth in Hunting Bayou, and a sixth at Westbury. Characteristics of each watershed are summarized in Table 3.

The Woodlands

The Woodlands sampling locations and their designations are listed below:

1. Panther Branch at the Confluence

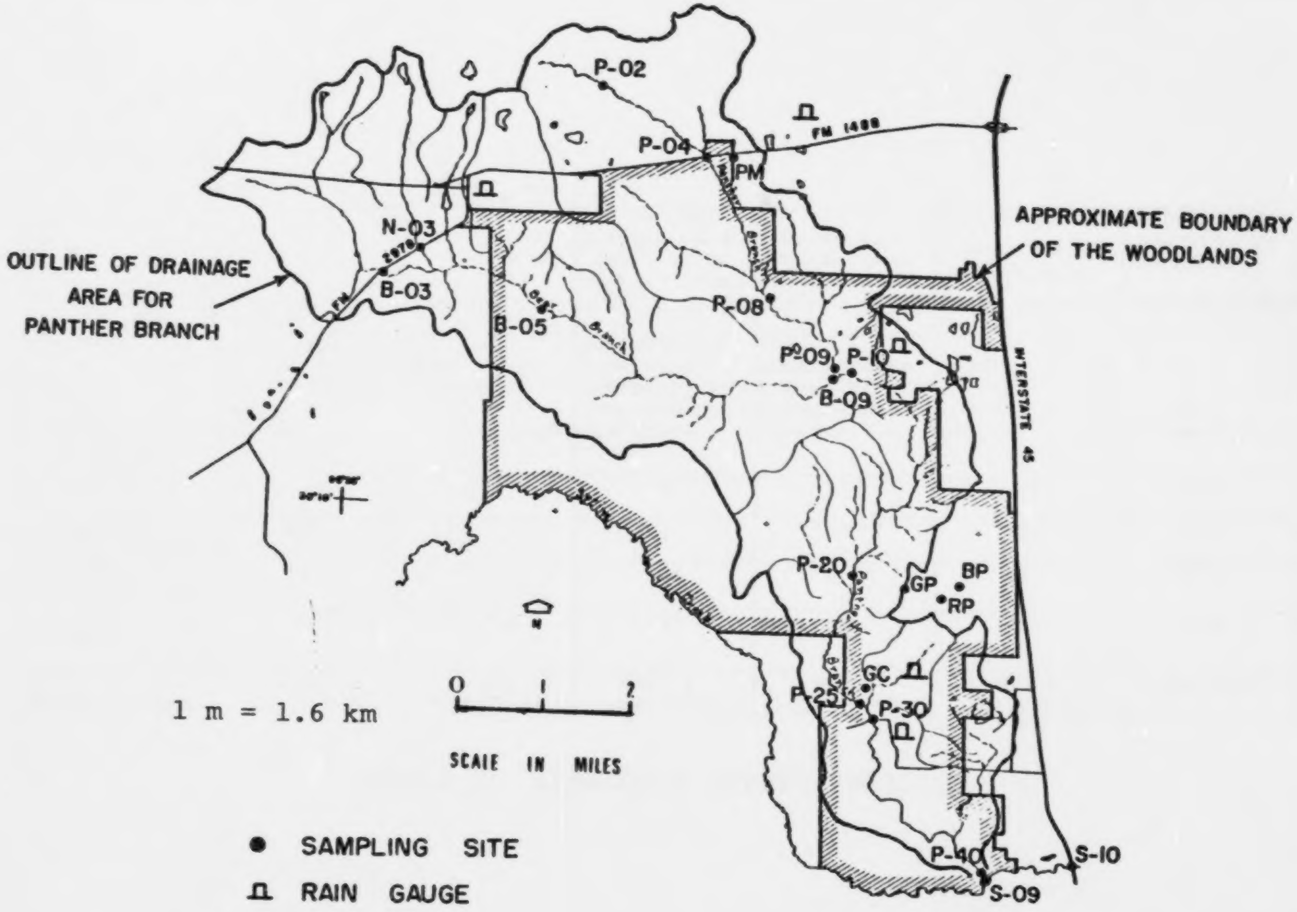

P-02
P-04
PM
FM 1488
APPROXIMATE BOUNDARY OF THE WOODLANDS
N-03
OUTLINE OF DRAINAGE AREA FOR PANTHER BRANCH
B-03
B-05
P-08
P-09
P-10
B-09
INTERSTATE 45
P-20
GP
BP
RP
GC
P-25
P-30
P-40
S-10
S-09
1 m = 1.6 km
0
1
2
SCALE IN MILES
● SAMPLING SITE
⊓ RAIN GAUGE

Figure 6. Location of sampling sites and rain gauges within the Panther Branch watershed.

TABLE 3. WATERSHED CHARACTERISTICS

Watershed and Sampling Site:	Woodlands P-30	Woodlands P-10	Woodlands Lake A	Woodlands Lake B	Hunting Bayou	Westbury
Drainage Area, acres	21,606	16,050	483	337	1976	210
Impervious Area	1%	<1%	13%	7.1%	21%	35.4
Area Storm Sewered	0	0	0	0	28%	100%
Land Slope	.16%	.20%	.3%	.3%	.1%	.08%
Land Use Classification	Natural forest land = 90%. Development and construction = 10%.	Natural Forest land = 99%. Developed land = 1%	Variable - Construction, Residential, Commercial & Recreational.	Variable - Construction, Residential % Recreational.	Residen. = 48% Commerc. = 32% Industr. = 14% Undevel. = 6%	Residential = 100%
Demographic Notes	Wildlife	Wildlife	Planned development: upper middle class residences & recreation.	Planned development: upper middle class residences.	Lower Income Population density = 12 persons/acre	Middle Class. Population Density= 11 persons/acre

1 ac = .405 ha

	with Bear Branch	P-10
2.	Panther Branch at Sawdust Road	P-30
3.	Outflow of Lake Harrison	Lake A
4.	Inflow of Lake Harrison	Lake B

A U.S.G.S. gauging station measured streamflow at each of these sites.

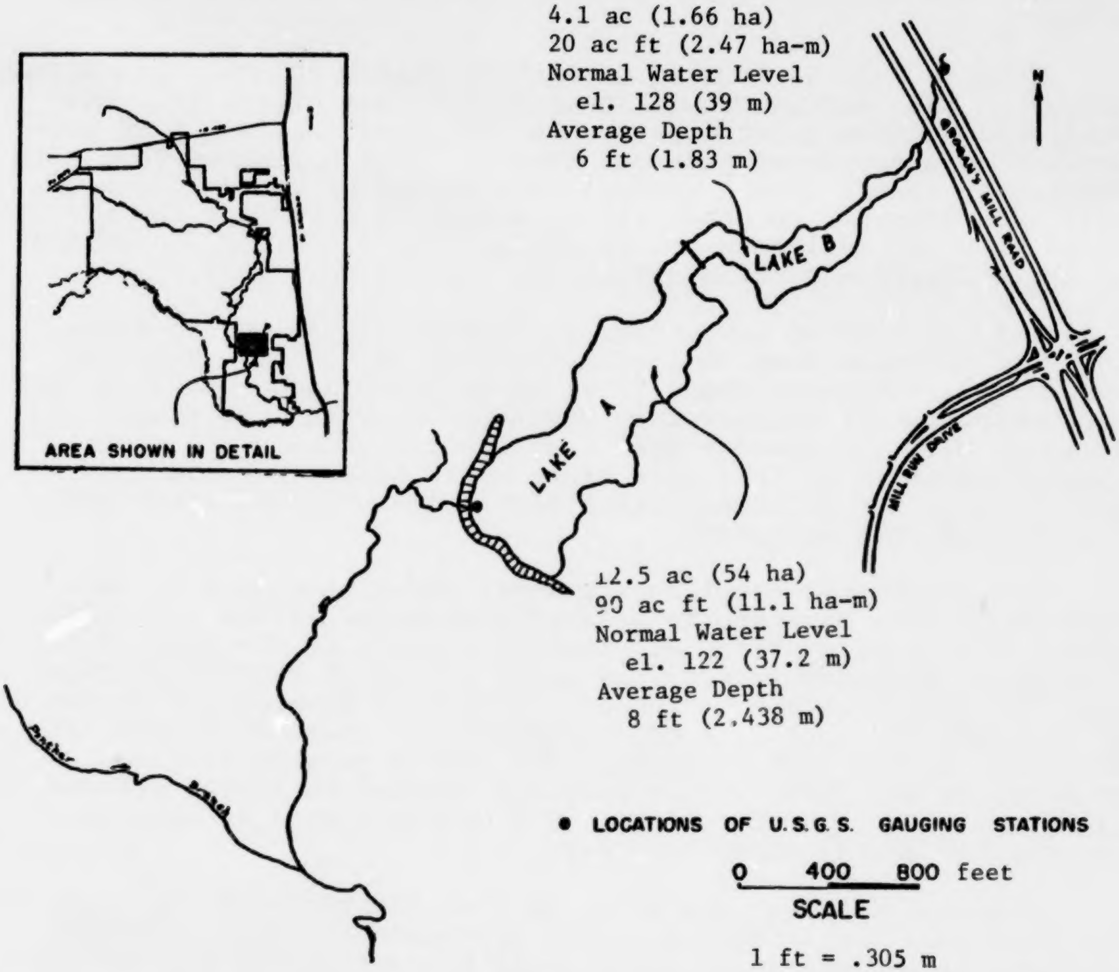
Station P-10 is located on Panther Branch 200 yds (182.9 m) downstream of the confluence with Bear Branch (see Figure 6). The watershed at this point measures 16,050 acres (6,495 ha) of predominantly undeveloped pine-oak forest. Data collected from P-10 represents runoff from a natural area devoid of urban influences and, when compared to other sites, serves to determine the effects of urban influences on runoff quality. U.S.G.S. established the streamflow gauging station at P-10 in July 1974.

P-30 is located downstream on Panther Branch and includes the P-10 drainage area in its 21,606 acre (8,744 ha) watershed (Figure 6). The sampling site is in an advantageous position for monitoring runoff quality from development areas immediately upstream. U.S.G.S. has operated a streamflow gauging and monthly sampling station at this site since April 1972. Because construction at The Woodlands was a continuing process, water quality changes were expected.

Two stormwater sampling stations, shown in Figure 7, were located at Lake Harrison to measure stormwater inflow and outflow. The upper station, situated in a swale at the head of Lake B, sampled runoff from the major source of stormwater flow into the lake system. During dry weather, no flow occurs in the swale. The 337 acre (136 ha) watershed was under extensive construction at the time of study. The Lake A gauging station, adjacent to the lake outflow box, was sampled to assess effects of detention on runoff quality. The drainage area at Lake Harrison outflow is 483 acres (196 ha).

Rainfall data was available at five locations in, or near, The Woodlands (see Figure 6). The precipitation data collected at these sites determined the average hyetograph for the Panther Branch watershed during each storm event and defined the intensity, duration, time period and total amount of rainfall. The rainfall network provided data on the spatial and temporal characteristics of rainfall within the study basin.

Runoff samples were analyzed for the same parameters listed in the dry weather flow program. Chemical data were used in conjunction with flow data to derive mass flow relationships for each constituent during each storm.


AREA SHOWN IN DETAIL
N
LAKE B
LAKE A
GROGAN'S MILL ROAD
MILL RUN DRIVE
Panther Branch
● LOCATIONS OF U.S.G.S. GAUGING STATIONS
0 400 800 feet
SCALE

4.1 ac (1.66 ha)
20 ac ft (2.47 ha-m)
Normal Water Level
el. 128 (39 m)
Average Depth
6 ft (1.83 m)

12.5 ac (54 ha)
90 ac ft (11.1 ha-m)
Normal Water Level
el. 122 (37.2 m)
Average Depth
8 ft (2.438 m)

1 ft = .305 m

1 ac = .405 ha

Figure 7. The Woodlands man-made lake system with locations of stormwater monitoring sites.

Hunting Bayou

The stormwater sampling program at Hunting Bayou was similar to The Woodlands, except that only one sampling site was monitored. Stormwater samples were collected from the U.S.G.S. Hunting Bayou at Falls Street gauging station (see Figure 4). Precipitation data were available from two recorders located south of the drainage basin.

Westbury

Runoff from this watershed was sampled above the Atwell Street bridge crossing the primary drainage channel (see Figure 5). Flow measurements were determined using a pygmy flow meter, and precipitation measurements were made using a portable volumetric gauge located at the sampling site.

Porous Pavement

The porous pavement parking lot at The Woodlands Conference Leisure and Commercial Center was finished October 1974. The pavement consists of a porous asphalt-concrete topping overlaying a gravel reservoir. Porous topping is produced from an asphalt bound aggregate deficient in fine sizes. In comparison to conventional toppings, increased amounts of asphalt are required to compensate for loss of strength resulting from the lower contact area between discrete particles of aggregate.

Soil permeability is poor at The Woodlands, so to simulate a reasonably permeable subsoil, the site of the porous pavement lot was excavated to a depth of 4 ft (1.2 m) and a permeable soil/sand mixture was filled into the excavation to a depth of 33.5 in. (85 cm). Open aggregate base course, 12 in. (30.5 cm) in depth was placed over the simulated subbase and 2.5 in. (6.6 cm) of porous topping was put down. A French drain was constructed to drain water from the soil/sand subbase.

The site plan for the experimental parking lot is shown in Figure 8. Stormwater samples were collected from the water depth wells in both conventional and porous lots. The quality of stormwater percolating through porous pavement was assessed and compared to conventional pavement runoff for the following chemical parameters: TP, orthophosphate, NH_3, NO_2, TKN, pH, conductance, soluble COD, lead, zinc, and total organic carbon (TOC).

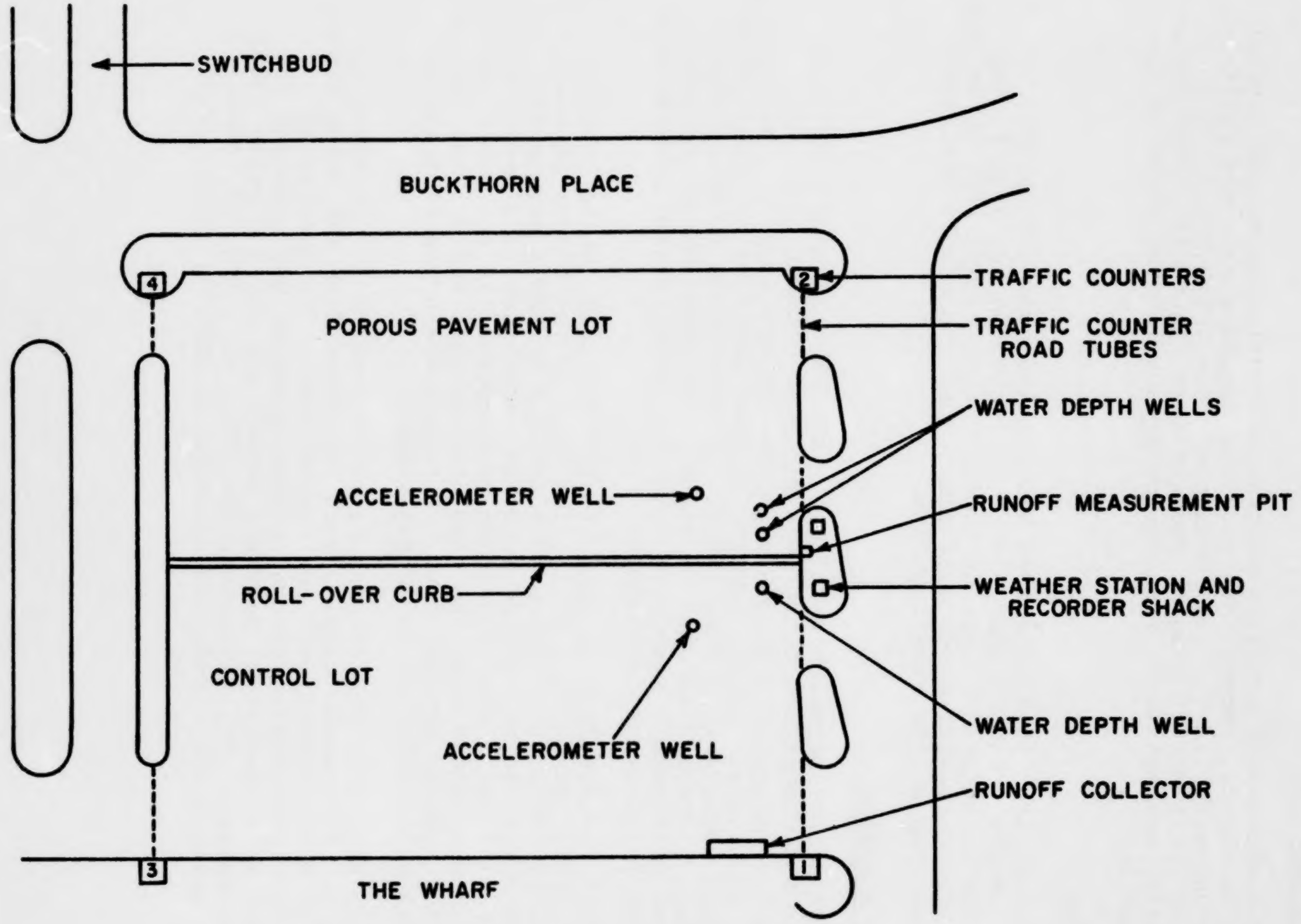

SWITCHBUD
BUCKTHORN PLACE
4
2
TRAFFIC COUNTERS
POROUS PAVEMENT LOT
TRAFFIC COUNTER ROAD TUBES
WATER DEPTH WELLS
ACCELEROMETER WELL
RUNOFF MEASUREMENT PIT
ROLL-OVER CURB
WEATHER STATION AND RECORDER SHACK
CONTROL LOT
WATER DEPTH WELL
ACCELEROMETER WELL
RUNOFF COLLECTOR
3
1
THE WHARF

Figure 8. Site plan for the porous pavement parking lot.

SECTION 6

RESULTS AND DISCUSSION

DATA SUMMARY

Dry Weather Monitoring

Surface water quality within The Woodlands was determined during dry weather periods to establish a baseline water quality. The baseline will be useful for determining (a) the effect of urbanization on the water resources of The Woodlands over the next 20 years, and (b) immediate comparisons between stormwater runoff quality and baseflow water quality. Woodlands sampling sites are indicated in Figure 6. Dry weather, or low flow, refers to time periods when the stream stage is essentially constant. The time period following a storm event required to establish low-flow conditions depends on factors such as antecedent moisture conditions, time since last storm, rainfall duration and intensity, and groundwater elevation. In the Panther Branch watershed, low-flow conditions were normally established 4-8 days after a storm event.

Low flow water quality data for Panther Branch, Bear Branch and Spring Creek are presented in Table 4. The headwaters in the stream system are low in inorganic nutrients but significant contributions from developing areas increase concentrations below P-10. The primary nutrient input is from the golf course immediately upstream of P-30. Organic concentrations are high (50 mg/l COD), consisting of relatively non-biodegradable (2 mg/l BOD) leachate from decaying vegetation in the forest. COD dilution occurred downstream and the lowest concentrations were observed in Spring Creek. TSS changed drastically as the stream passed through developing areas where construction activity and borrow pits were located in the floodplain. Low flow TSS as high as 1600 mg/l were observed at P-30.

Storm Events

Data characterizing hydrological, physical, and chemical aspects of 43 distinct runoff events resulted from 17 selected rainfall periods with streamflow being sampled simultaneously at one to four of the monitoring stations established by Rice University (refer to Site Description, Section 4). The number of

TABLE 4. SUMMARY OF LOW-FLOW WATER QUALITY PARAMETERS, AVERAGE CONCENTRATIONS (not weighted).

	Bear & Panther Branch above P-10	P-10 Sampling Site	Panther Br. between P-10 and P-30	P-30 Sampling Site	Spring Creek
TP	0.067	0.064	0.10	0.135	0.232
Ortho P	0.025	0.029	0.053	0.049	0.12
TKN	0.85	0.932	1.0	1.166	0.71
NH_4	0.116	0.0932	0.184	0.203	0.198
NO_2	0.006	0.0054	0.006	0.0054	0.015
NO_3	0.026	0.0244	0.029	0.059	0.359
TSS	16.45	22.6	83.0	80.7	38.3
Turbidity	12.0	14.7	46.0	41.2	30.3
Specific Conductivity	30.	46.	58.	102.	147.
SOC	23.0	19.9	19.0	15.5	19.2
Total COD	54.3	50.0	52.0	51.0	26.4
Soluble COD	40.7	40.6	40.0	37.4	19.3
BOD	2.0	1.75	1.8	2.1	1.4
pH	6.4	6.28	6.6	6.39	6.7
DO	5.5	5.23	4.8	4.27	6.7
Temp.	19.0	17.9	20.0	18.6	19.2
Discharge	1.46	3.04	2.0	5.16	116.0

Note: All measurements in mg/l except: Discharge, cfs; Turbidity, JTU; Specific Conductivity, micromhos/cm; pH, pH units; Temperature, °C.

1 cfs = .0079 L/S

runoff events monitored at each sampling site were as follows:

Sampling Site	Number of Runoff Events
P-30	12
P-10	8
Lake A	8
Lake B	8
Hunting Bayou	5
Westbury Square	2

Hydrological Observations--

A summary of the hydrological data is presented in Table 5. Hydrological parameters are specifically defined in Table 6. Note that Total Streamflow is the sum of Baseflow and Runoff. The number of storm events monitored was limited by two drought periods, each of six month duration during the project.

Rainwater Quality--

Previous investigations indicate air pollution may contribute to surface water pollution through rainfall and/or dry fallout, even to the extent of pollutants traveling via air from industrial and agricultural regions to be deposited in undeveloped areas (37, 38). Samples collected in the Houston area and at The Woodlands assessed relative contributions of rainwater quality to stream pollution. Results presented in Table 7 indicate a substantial nutrient and COD content in rainwater at both sites. A statistically significant increase exists between Houston and The Woodlands rainwater in regard to NH_3 and NO_3 content. The rainwater data are compared to stormwater data in Table 8. A study of air quality at The Woodlands indicated high levels of hydrocarbons, 7.6 ppm non-methane hydrocarbons, whose source was attributable to vegetative emissions. These ambient air hydrocarbons may contribute to the soluble COD in rainwater. The study also found an absence of NO_x at The Woodlands in contrast to serious NO_x air pollution problems in the Houston urban area (39).

At The Woodlands, rainwater nutrient concentrations were greater than runoff water, while the opposite relationship prevalied in the urban watershed. Experiments were conducted to determine the capacity of soils for stormwater nutrient removal. Four samples of soil from various locations in The Woodlands (see below) were dried and weighed. The samples were extracted with demineralized water until no further NH_3 was measured in the extract, and then equilibrated with 30 ml portions of 1 mg N/l (ammonium sulfate). After centrifugation, the supernatant was analyzed for NH_3 and then discarded. This was repeated until no further adsorption was measured. Findings indicate low levels of NH_3 are definitely adsorbed by soils, with the greatest

TABLE 5. STORM EVENT HYDROLOGY SUMMARY

#	Date	Site	Rainfall, inches	Total Stream-flow, acre-ft[a]	Base Flow, CFS	Base Flow acre-ft.	Peak Flow, CFS	Runoff, acre-ft	Runoff Coefficient[b]	Antecedent Rain Week	Antecedent Rain Month, in.
1	1/18/74	Woodlands P-30	2.02	2334.0	40.0	203	1260.0	2131.0	53.0	1.65	8.0
2	3/20/74	Hunting Bayou	0.15	2.507	5.0	1.6	9.6	0.857	3.3	1.53	2.06
3	3/26/74	Hunting Bayou	0.75	42.06	9.5	17.	40.0	24.8	20.0	1.25	3.03
4	4/11/74	Hunting Bayou	0.35	12.41	4.0	6.9	11.0	5.47	9.4	0.0	3.73
5	4/22/74	Woodlands P-30	0.45	5.8	0.2	0.40	9.7	5.39	.7	0.18	2.87
6	10/28/74	Woodlands P-30	3.46	937.0	1.6	8.6	382.0	928.4	15.0	0.08	1.53
7	12/05/74	Woodlands P-30	1.59	1267.0	4.5	29.	332.0	1238.0	43.0	0.24	6.79
		Woodlands P-10	1.52	833.0	2.1	11.	280.0	822.0	40.0	0.27	7.71
8	3/04/75	Woodlands P-30	0.33	3.318	1.75	1.5	4.9	1.8	0.3	0.0	1.18
		Lake A	0.26	No Discharge		-		-	-	0.0	2.39
		Lake B	0.26	0.135	0.0	0	0.38	0.135	1.8	0.0	2.39
9	3/13/75	Woodlands P-30	0.75	119.0	1.3	7.7	49.0	111.0	2.2	0	0.38
		P-10	0.69	79.09	0.64	2.1	56.0	77.0	8.3	0	0.34
		Lake A	0.81	2.38	0.0	-	2.0	2.38	7.3	0.26	0.31
		Lake B	0.81	1.77	0.0	0	12.7	1.77	7.7	0.26	0.31
10	4/08/75	Woodlands P-30	2.76	2829.0	0.48	2.9	1100.0	2826.0	56.8	0.0	2.56
		P-10	2.43	1614.0	1.0	4.0	1170.0	1610.0	49.5	0.0	2.54
		Lake A	3.97	93.39	0.0	0	114.0	93.4	58.0	0.0	2.24
		Lake B	3.97	93.2	0.0	0	123.0	93.2	84.0	0.0	2.24
11	5/08/75	Hunting Bayou	0.81	28.9	4.6	5.13	72.5	23.8	17.7	0.71	4.21
		Westbury	0.75	7.16	0.0	0	36.0	7.16	54.0		

(Continued)

1 in = 2.54 cm
1 ac = .105 ha
1 ft = .305 m
1 cfs = .028 m^3/sec

TABLE 5 (continued)

#	Date	Site	Rainfall inches	Total Stream-flow, acre-ft[a]	Base Flow, CFS	Base Flow acre-ft.	Peak Flow, CFS	Runoff, acre-ft	Runoff Coefficient[b]	Antecedent Rain Week	Antecedent Rain Month, in.
12	06/30/75	Hunting Bayou	1.85	115.7	14	22.	136	94.0	31.0	5.26	9.37
		Westbury	1.28	11.23	0	0	47	11.23	50.0	1.31	11.9
13	09/05/75	Woodlands P-30	.35	9.825	0.14	0.34	10.3	9.48	1.5	.74	1.95
		Woodlands P-10	.25	0.918	0.02	.10	0.38	0.822	0.16	.84	2.23
		Lake A	1.11	No Discharge	0	0	---	0	0	.39	.78
		Lake B	1.11	1.51	0	0	8.8	1.51	4.7	.39	.78
14	10/25/75	Woodlands P-30	2.89	117.35	0	0	64	117.35	2.3	.18	.85
		Woodlands P-10	2.82	57.09	0	0	22	57.09	1.5	.18	.85
		Lake A	3.37	18.86	0	0	15	18.86	14.0	.10	.98
		Lake B	3.37	No Data	-	-	-	-	-	.10	.98
15	03/07/76	Woodlands P-30	.713	14.88	1.45	1.3	18.5	12.6	0.9	.48	1.04
		Woodlands P-10	.68	11.24	.3	0.87	7.9	10.37	1.13	.41	1.05
		Lake A	.69	No Discharge	-	0	-	6.5	0	.98	1.42
		Lake B	.69	0.884	0	0	3.8	.884	5.0	.98	1.42
16	03/08/76	Woodlands P-30	.53	99.3	8.4	40.	32.5	59.0	6.2	1.19	1.75
		Woodlands P-10	.48	58.3	5.3	29.	23	29.1	4.5	1.09	1.73
		Lake A	.71	6.78	0	0	3.4	6.78	24.0	1.68	2.07
		Lake B	.71	2.71	0	0	6.6	2.71	13.6	1.68	2.07
17	04/04/76	Woodlands P-30	.366	45.95	.18	0.39	64	45.56	6.9	.05	2.08
		Woodlands P-10	.29	.764	.11	0.23	.37	0.537	0.1	.05	1.83
		Lake A	1.17	14.54	0	0	10	14.53	31.0	.08	3.25
		Lake B	1.17	5.10	0	0	19	5.103	15.0	.08	3.25

---

[a] Total streamflow is calculated to include components of overland runoff and base flow.

[b] Percentage of rainfall as runoff.

1 in = 2.54 cm
1 ac-ft = .123 ha-m
1 cfs = .028 m^3/sec

TABLE 6. HYDROLOGICAL DEFINITIONS AND CALCULATIONS

Storm Event:	Discrete period of rainfall producing runoff monitored during the study.
Total Rainfall:	Calculated via Thiessen method using total precipitation data recorded over 2 separate drainage areas, P-10 and P-30. The coefficients are calculated using these rain gauges: Porous Pavement, Egypt, Confluence and W. G. Jones.

P-30 Drainage Area		P-10 Drainage Area	
Porous P.	- .125	Confluence	- .258
Confluence	- .328	Jones	- .100
Jones	- .075	Egypt	- .642
Egypt	- .472		

Duration of Rainfall:	Shortest time period during which 85% of total precipitation occurred.
Rainfall Intensity:	Total rainfall divided by duration.
Type of Storm Event:	Described type of rainfall - e.g. one period of rainfall, 2 periods of rainfall, etc.
Antecedent Rainfall Condition:	Total precipitation in 1 week period prior to storm event. Calculate same way as Total Rainfall (see above).
Total Discharge or Flow:	Volume of storm event hydrograph.
Runoff:	Overland flow volume. Equal to total discharge minus base flow.
Peak Flow:	Maximum stream discharge.
Base Flow or Groundwater Flow:	Calculated by multiplying the instantaneous discharge prior to the storm event by the time of passage.
Time of Passage:	Time from first rise in stream to 0.1 of the peak flow. If the hydrograph does not return to this level due to successive rainfall a hydrograph separation technique is used to extend the recession limb to 0.1 of the peak. When runoff is minimal and base flow greater than 0.1 of peak flow, then the inflection point on the hydrograph tail is assumed the end of passage.
Time of Concentration:	Time from first rise in stream to peak flow.

TABLE 7. RAINWATER QUALITY ANALYSIS

	Constituent											
Site	NH_4			NO_3			Ortho PO_4			Soluble COD		
	[1]$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	n
Houston[2]	0.31	0.12	85	0.52	0.56	111	.012	.014	52	14.1	13.7	69
	$p < .05$[4]			$p < .05$			N.S.			N.S.		
Woodlands[3]	0.22	0.09	19	0.31	0.17	20	.039	.056	19	15.4	7.07	20

1. $\bar{x}$ = mean values in mg/l, s = standard deviation, n = number of samples.
2. Rain samples collected at Rice University on 7/11/75, 7/23/75, 8/12/75.
3. Rain samples collected at The Woodlands on 11/19/75,2/20/76.
4. Student "t" test using Welch approximations. $p = .05$ level of significance.
   N. S. = not significant.
   (Remington and Schork, Statistics with Applications to the Biological and Health Sciences. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1970.

TABLE 8. COMPARISON OF RAINWATER AND RUNOFF QUALITY IN HOUSTON AND AT THE WOODLANDS (ALL UNITS IN mg/l)

Constituent	Houston		The Woodlands	
	Rain	Runoff[1]	Rain	Runoff[2]
soluble COD	14	20	15	44
NH_3	.31	2.1	.22	.08
NO_3	.52	.38	.31	.05
ortho P	.01	.57	.04	.005

[1] Avg. of stormwater data collected at Hunting Bayou

[2] Avg. of stormwater data collected at P-10

adsorption occurring in undisturbed forest soil:

Soil Sample	Total mg N/g Adsorbed[1]
Golf Course	0.027
Roadside	0.022
Swale	0.017
Woods	0.043

[1] mg N/g dry soil adsorbed in equilibrium with 1 mg N/l solution of ammonium sulfate.

The data suggest that ammonia nitrogen in rainwater is adsorbed to a large extent in undisturbed forest soils where it is metabolized by plants or nitrified and possibly denitrified by soil microorganisms. In an urban area receiving the same ammonia rainwater load, there is more impervious area resulting in higher ammonia in the runoff. In addition, soils in an urban area have a lower NH_3 adsorption capacity and lower NH_3 utilization rate.

Of greatest significance is the effect of nutrient wash off on lake eutrophication at The Woodlands. Ward and King (40) have shown nitrogen to be the limiting nutrient for algal growth in The Woodlands lakes during wet weather. As development continues, increasing nitrogen input from stormwater runoff can be expected and lake enrichment may result.

Groundwater Quality--

Surface water quality at The Woodlands is influenced by infiltration from the perched water table. To determine groundwater quality, samples were collected from 17 wells located within the watershed 3 days after a 2.8 in. (7.1 cm) rainfall. The wells consist of 2 in. (5 cm) I.D. PVC pipe driven 2 to 5 ft. (0.6 to 1.5 m) into the soil. Results presented in Table 9 indicate The Woodlands groundwater contains greater amounts of nutrients but less organic material than runoff. Low pH values are consistent with the naturally acid soil due to the presence of humic and tannic components, high clay and low carbonate content.

TABLE 9. COMPARISON OF GROUNDWATER QUALITY AFTER RAINFALL TO RUNOFF WATER QUALITY

Constituent[1]	Groundwater[2]	Runoff[3]
TKN	2.1	1.37
NH_3	1.4	0.08
TP	0.09	0.06
Ortho P	0.02	0.003
pH	5.1	5.9
Specific Conductance	200	110
Total COD	22	59
SOC	10	22

[1] Data in mg/l except specific conductance as micromhos/cm and pH in pH units.

[2] Mean concentrations of samples collected within 3 days of 2.8 inch rainfall on April 14, 1975.

[3] Mean concentrations for runoff samples collected at P-10 during April 8, 1975 storm event.

Stormwater Runoff Quality--

Discrete water samples were collected for the purpose of defining temporal stormwater quality during a storm. Over 850 stormwater samples were collected and over 12,000 separate water quality analyses were performed. A summary of the water quality data is presented in Table 10, including mass load and flow weighted mean concentrations for each parameter. Mean concentrations are calculated from discrete sample results weighted according to instantaneous stream discharge at the time of collection. Mass load represents total amount of constituent passing the monitoring site during the runoff event. Mass load is incalculable where no discharge occurred, as with lake storage of stormwater.

All water quality samples collected are representative of the total streamflow volume (including baseflow) which is reported in Table 10. In the majority of events, overland runoff is approximately equal to total streamflow and samples can be considered representative of runoff. For storm events producing low runoff, water quality is influenced by baseflow.

Chlorinated Hydrocarbons

During the two-and-one-half-year study some 2500 biotic and abiotic samples were collected in The Woodlands and analyzed for halogenated hydrocarbon compounds. The major sampling emphasis was directed toward surface waters and aquatic fauna, however soil-sediment and plant samples were also analyzed.

Polychlorinated Biphenyls--

The major class of chlorinated compounds detected during the study was the polychlorinated biphenyls (PCBs). These formulations are used in a variety of industrial applications such as varnishes, paints, inks, waxes, flooring tile, synthetic rubber and asphalt; however, greatest usage is in the electronics industry in the production of capacitors and transformers. PCBs have been produced for over 40 years but only recently have they been observed as a pollutant in the environment.

The temporal distribution of PCBs in The Woodlands surface waters and soils is presented in Figure 9. In January 1974 a sudden increase in PCB concentrations in soils was observed which was followed by a rise in surface water concentrations some four months later. The rates of decline of both of these peak concentrations resemble a first order curve. No further increase in PCBs in water was observed throughout the remainder of the study. By extracting larger amounts of soil and concentrating the compounds on activated charcoal followed by elution and subsequent analysis, a second minor peak, three orders of magnitude lower, was observed in soil samples during the spring of 1975. Several plant samples were found to contain trace amounts of PCBs, but the minute amounts could have been due to surface contamination since they coincided with the highest values observed in water and soil samples. The level of PCBs in aquatic animal samples started rising in late 1973 and reached a peak in April of 1974 (Figure 10), which is coincident with the highest concentrations in the water samples (Figure 9). The concentration in the aquatic organisms is about 10 times that in the water samples but 1/10 that observed in the soil samples (Figure 9).

TABLE 10. RUNOFF WATER QUALITY SUMMARY-- MASS FLOW AND WEIGHTED AVERAGE

Storm #	Date	Site	Streamflow acre-feet	Ortho-PO_4		TP		NH_3	
				lb	$\bar{x}$ conc mg/l	lb	$\bar{x}$ conc mg/l	lb	$\bar{x}$ conc mg/l
1	01/18/74	The Woodlands P-30	2334	7.73	.001	No Data		215.	.034
2	03/20/74	Hunting Bayou	2.51	2.96	.437	No Data		16.5	2.44
3	03/26/74	Hunting Bayou	42.1	45.1	.395	46.4	.407	287.	2.51
4	04/11/74	Hunting Bayou	12.4	16.9	.503	30.3	.899	24.6	.732
5	04/22/74	The Woodlands P-30	5.80	0.70	.044	7.53	.478	5.27	.334
6	10/28/74	The Woodlands P-30	937.	43.0	.017	256.	.101	236.	.093
7	12/05/74	The Woodlands P-30	1267	33.7	.010	328.	.096	355.	.103
		The Woodlands P-10	833.	14.1	.006	171.	.076	199.	.088
8	03/04/75	The Woodlands P-30	3.32	0.23	.025	1.14	.127	.880	.100
		Lake A	Stored	NA	.008	NA	.097	NA	.062
		Lake B	.135	.012	.033	.077	.210	.238	.650
9	03/13/75	The Woodlands P-30	119.	3.15	.010	52.3	.162	22.2	.069
		The Woodlands P-10	79.1	1.15	.005	19.7	.092	19.2	.089
		Lake A	2.38	.043	.006	.893	.137	.760	.117
		Lake B	1.77	.102	.021	2.54	.530	1.06	.221
10	04/08/75	The Woodlands P-30	2829	85.2	.011	675.	.088	1144	.149
		The Woodlands P-10	1614	15.0	.003	264.	.060	339.	.077
		Lake A	93.4	3.75	.015	26.2	.103	39.6	.156
		Lake B	93.2	1.25	.005	27.9	.110	28.1	.110
11	05/08/75	Hunting Bayou	28.9	40.4	.516	84.2	1.08	94.4	1.20
		Westbury	7.16	13.8	.710	14.2	.730	17.3	.890

NA - Not applicable - a mass loading was not calculable.
Stored - No discharge of stormwater from the lake system.

Note: ac-ft = .123 ha-m
lb = .4536 kg

(continued)

TABLE 10 (continued)

NO_2		NO_3		TKN		TSS		SOC		Total COD		Soluble COD	
lb	$\bar{x}$ conc mg/l	lb	$\bar{x}$ conc mg/l	lb $\times 10$	$\bar{x}$ conc mg/l	lb $\times 10^3$	$\bar{x}$ conc mg/l	lb $\times 10^2$	$\bar{x}$ conc mg/l	lb $\times 10^2$	$\bar{x}$ conc mg/l	lb $\times 10^2$	$\bar{x}$ conc mg/l
5.30	.001	181.	.029	No Data		1492	236.	No Data		No Data		No Data	
.353	.052	2.96	.438	No Data		.480	70.9	2.59	38.3	5.18	76.6	No Data	
7.42	.065	58.1	.509	40.1	3.52	22.5	197.	18.5	16.3	114.	99.8	No Data	
2.18	.065	11.4	.338	5.25	1.56	4.10	122.	18.6	55.3	34.3	102.	10.8	32.0
.170	.011	3.71	.235	2.11	1.34	14.8	939.	2.74	17.4	14.7	93.1	8.53	54.2
12.5	.005	94.2	.037	No Data		775.	305.	455.	17.9	No Data		859.	33.8
18.5	.005	79.9	.023	311.	.905	296.	86.2	No Data		1962	57.1	1405	40.9
.280	.000	27.6	.012	187.	.826	60.5	26.8	No Data		1400	62.0	988.	43.7
.055	.006	.960	.107	1.50	1.66	.426	47.0	.802	9.00	3.02	33.4	2.88	32.0
NA	.008	NA	.189	NA	.829	NA	166.	NA	14.0	NA	47.0	NA	32.5
.016	.044	.131	.357	.066	1.79	.104	283.	.027	7.35	.181	49.2	.120	32.6
1.08	.003	35.9	.111	35.1	1.09	28.8	90.0	69.8	21.6	192.	59.3	143.	44.2
.750	.003	22.1	.103	34.5	1.61	14.4	67.0	48.2	22.5	136.	63.4	111.	51.9
.065	.010	1.32	.203	.401	.620	.991	152.	.900	13.8	2.47	38.0	1.87	28.8
.113	.024	1.74	.362	1.99	4.14	13.8	2877	.705	14.7	5.90	123.	1.37	28.5
73.1	.009	1181	.154	1065	1.39	1312	171.	1563	20.4	4037	52.6	2981	38.8
17.1	.004	284.	.065	600.	1.37	168.	38.5	962.	22.0	2572	58.8	1888	43.1
8.24	.032	70.4	.280	33.3	1.31	61.9	245.	34.4	13.6	106.	41.8	66.8	26.4
2.18	.009	37.6	.150	47.1	1.86	322.	1273	40.8	16.2	161.	63.7	82.0	32.0
4.52	.058	40.1	.511	25.5	3.25	16.2	207.	13.7	17.5	140.	179.	27.5	35.1
.754	.039	7.20	.371	4.25	2.19	.474	24.4	3.13	16.1	10.4	53.8	6.09	31.4

(continued)

TABLE 10 (continued)

Storm #	Date	Site	Streamflow acre-feet	Ortho-PO_4		TP		NH_3	
				lb	$\bar{x}$ conc mg/l	lb	$\bar{x}$ conc mg/l	lb	$\bar{x}$ conc mg/l
12	06/30/75	Hunting Bayou	116.	212.	.677	403.	1.28	660.	2.10
		Westbury	11.2	17.1	.560	34.6	1.14	4.40	.145
13	09/05/75	The Woodlands P-30	9.82	1.67	.063	4.75	.180	5.36	.201
		The Woodlands P-10	.918	.051	.021	.082	.033	.075	.030
		Lake A	Stored	NA	.011	NA	.050	NA	.069
		Lake B	1.51	.148	.035	.608	.148	.567	.138
14	10/25/75	The Woodlands P-30	117.	12.0	.038	46.7	.147	26.1	.082
		The Woodlands P-10	57.1	.342	.002	7.32	.047	8.34	.054
		Lake A	18.9	.068	.001	1.35	.026	2.27	.044
		Lake B	No Data	NA	.027	NA	.081	NA	.108
15	03/07/76	The Woodlands P-30	14.9	1.18	.029	No Data		2.58	.064
		The Woodlands P-10	11.2	.039	.003	No Data		1.67	.055
		Lake A	Stored	NA	.005	No Data		NA	.063
		Lake B	.884	.124	.052	No Data		.089	.037
16	03/08/76	The Woodlands P-30	99.3	7.92	.029	No Data		46.8	.174
		The Woodlands P-10	58.3	.217	.001	No Data		3.61	.023
		Lake A	6.78	.131	.007	No Data		.723	.039
		Lake B	2.71	.088	.012	No Data		.247	.034
17	04/04/76	The Woodlands P-30	45.9	5.38	.043	18.7	.149	48.9	.390
		The Woodlands P-10	2.83	.027	.003	.468	.061	1.21	.158
		Lake A	14.5	.148	.004	2.49	.063	4.79	.121
		Lake B	5.10	.077	.006	1.07	.078	1.66	.120

NA - Not applicable - a mass loading was not calculable.
Stored - No Discharge of stormwater from the lake system.

Note: ac-ft = .123 ha-m
1b = .4536 kg

(continued)

TABLE 10 (continued)

NO_2		NO_3		TKN		TSS		SOC		Total COD		Soluble COD	
lb	$\bar{x}$ conc mg/l	lb	$\bar{x}$ conc mg/l	lbs x10	$\bar{x}$ conc mg/l	lb $x10^3$	$\bar{x}$ conc mg/l	lb $x10^2$	$\bar{x}$ conc mg/l	lb $x10^2$	$\bar{x}$ conc mg/l	lb $x10^2$	$\bar{x}$ conc mg/l
14.0	.044	117.	.373	124.	3.94	51.0	182.	71.6	22.8	252.	80.4	61.2	19.5
.803	.026	11.8	.388	4.51	1.48	2.13	69.8	5.09	16.7	11.8	38.9	4.36	14.3
.480	.018	8.13	.305	1.16	.435	2.67	100.	No Data		No Data		9.40	35.2
.007	.002	.075	.030	.024	.097	.016	6.54	No Data		No Data		.852	34.5
NA	.009	NA	.009	NA	.172	NA	24.0	No Data		No Data		NA	19.5
.047	.012	.955	.233	.168	.410	6.70	1633	No Data		No Data		.878	21.4
1.56	.005	47.0	.147	9.69	.305	53.8	169.	66.0	20.7	135.	42.4	77.0	24.2
.690	.005	4.67	.030	4.04	.261	1.18	7.60	37.8	24.4	70.0	45.1	58.9	38.0
.143	.003	1.19	.023	.942	.184	1.85	36.2	2.38	4.66	10.9	21.2	7.21	14.1
NA	.010	NA	.113	NA	.280	NA	421.	NA	20.6	NA	48.9	NA	24.2
.593	.015	10.2	.252	No Data		9.55	237.	5.55	13.7	No Data		12.2	30.2
.321	.010	1.43	.047	No Data		6.47	212.	6.72	22.0	No Data		14.2	46.6
NA	.011	NA	.076	No Data		NA	184.	NA	8.00	No Data		NA	15.4
.035	.014	.393	.164	No Data		1.77	738.	.322	13.4	No Data		.631	26.3
3.70	.014	48.0	.178	No Data		78.1	290.	42.4	16.0	No Data		88.3	32.8
1.66	.011	3.69	.023	No Data		20.6	130.	41.4	26.0	No Data		86.6	54.7
.225	.012	1.64	.089	No Data		3.27	177.	1.11	6.05	No Data		2.73	14.8
.328	.045	1.31	.141	No Data		3.07	419.	.962	13.1	No Data		1.78	24.3
2.13	.017	52.9	.420	25.5	2.04	No Data		18.5	14.8	61.7	49.3	43.3	34.6
.052	.007	1.04	.135	.516	.672	No Data		1.27	16.5	3.08	40.0	2.97	38.7
.205	.005	4.53	.112	2.90	.735	No Data		3.98	10.1	7.88	20.0	9.20	23.3
.163	.012	4.92	.355	1.29	.929	No Data		1.94	13.3	6.00	43.3	5.15	37.2

(continued)

TABLE 10 (continued)

Storm #	Date	Site	Turbidity	pH	Temp.	Spec. Cond.	DO	Total Solids	BOD
1	01/18/74	The Woodlands P-30	150	6.5	14.7	-	9	-	-
2	03/20/74	Hunting Bayou	-	-	20	-	2.5	-	17
3	03/26/74	Hunting Bayou	135	-	15	-	4.6	-	-
4	04/11/74	Hunting Bayou	100	6.5	22	545	2.25	-	22
5	04/22/74	The Woodlands P-30	305	6.5	22	200	3.5	-	-
6	10/28/74	The Woodlands P-30	250	5.7	-	110	-	450	6.1
7	12/05/74	The Woodlands P-30	65	6.0	-	58	-	385	-
		P-10	20	5.2	-	56	-	110	-
8	03/04/75	The Woodlands P-30	35	7.5	14	375	8.3	-	-
		Lake A	121	7.5	16	115	7.8	-	-
		Lake B	184	8.1	-	415	7.6	-	-
9	09/13/75	The Woodlands P-30	50	6.6	13.5	280	6.4	-	-
		P-10	30	6.1	13.3	290	7.2	-	-
		Lake A	105	7.5	17	160	7.7	-	-
		Lake B	1200	7.8	11.5	185	7.4	-	-
10	04/08/75	The Woodlands P-30	130	6.8	-	103	7.8	-	-
		P-10	28	5.9	19	110	6	-	-
		Lake A	165	7.54	20	140	7.65	-	-
		Lake B	330	6.9	20	80	7.1	-	-
11	05/08/75	Hunting Bayou	110	7.6	24	460	3.2	-	-
		Westbury Square	18	7.3	-	175	3.34	-	-
12	06/30/75	Hunting Bayou	140	7.2	27	360	3.3	-	-
		Westbury Square	14	7.3	-	125	4.6	-	-
13	09/05/75	The Woodlands P-30	100	7.05	-	208	-	-	-
		P-10	7	6.6	-	280	-	-	-
		Lake A	19	8.01	-	336	-	-	-
		Lake B	830	7.6	-	135	-	-	-
14	10/25/75	The Woodlands P-30	120	7.4	18.5	275	7.5	-	-
		P-10	12	5.8	18	247	6.6	-	-
		Lake A	24	8.1	22	536	8.2	-	-
		Lake B	325	7.4	19	167	7.6	-	-
15	03/07/76	The Woodlands P-30	74	-	-	281	-	-	-
		P-10	12	-	-	410	-	-	-
		Lake A	-	-	-	-	-	-	-
		Lake B	137	-	-	155	-	-	-
16	03/08/76	The Woodlands P-30	138	-	-	-	-	-	-
		P-10	5	-	-	365	-	-	-
		Lake A	-	-	-	410	-	-	-
		Lake B	120	-	-	115	-	-	-
17	04/04/76	The Woodlands P-30	70	7.3	-	318	-	-	-
		P-10	7	6.9	-	284	-	-	-
		Lake A	53	7.9	-	363	-	-	-
		Lake B	110	7.2	-	125	-	-	-

All measurements in mg/l except: Turbidity in JTU; pH in pH units; Temperature in Centigrade and Specific Conductance in micromhos/cm.

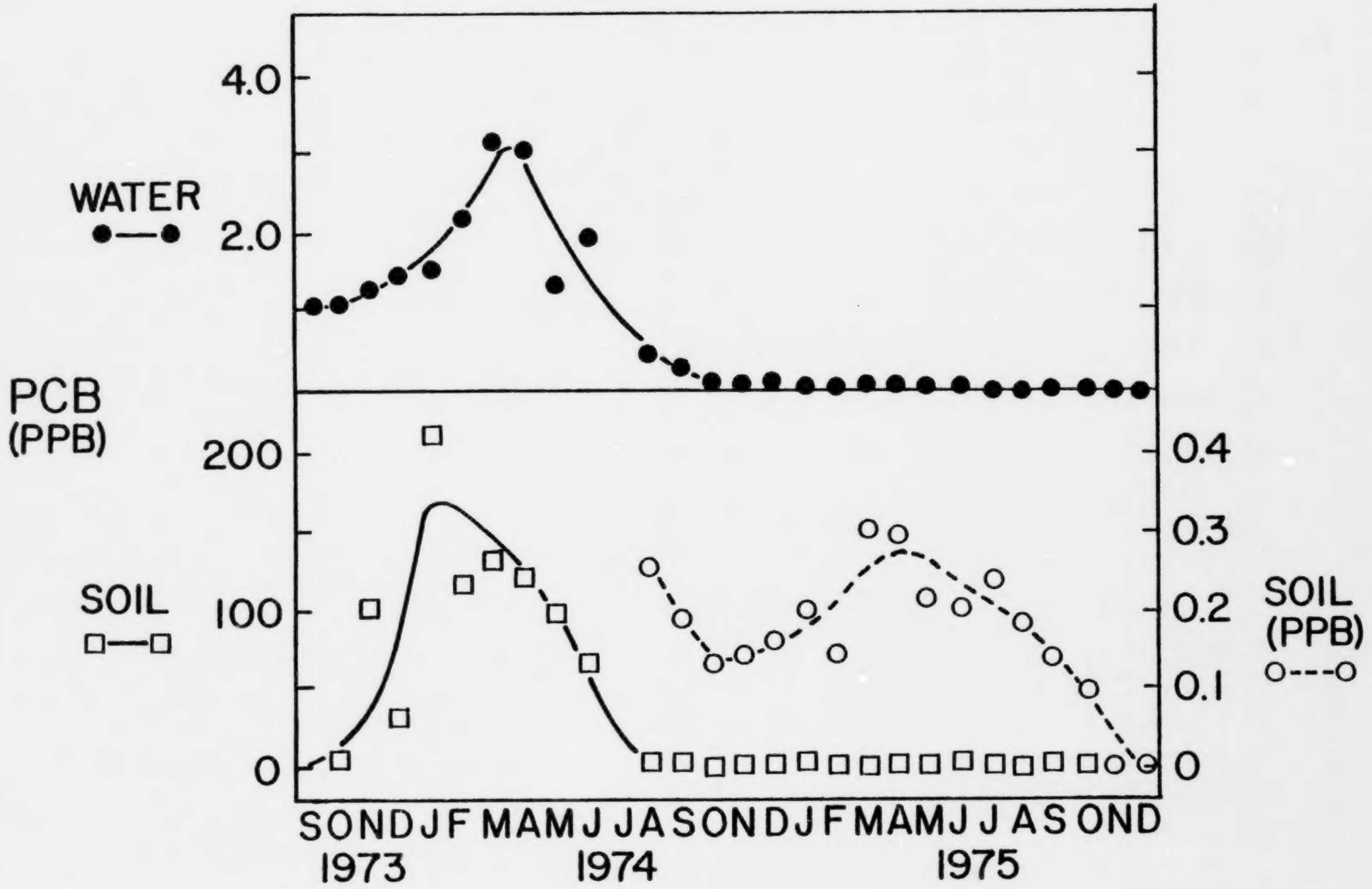


Figure 9. Temporal distribution of polychlorinated biphenyls in The Woodlands.

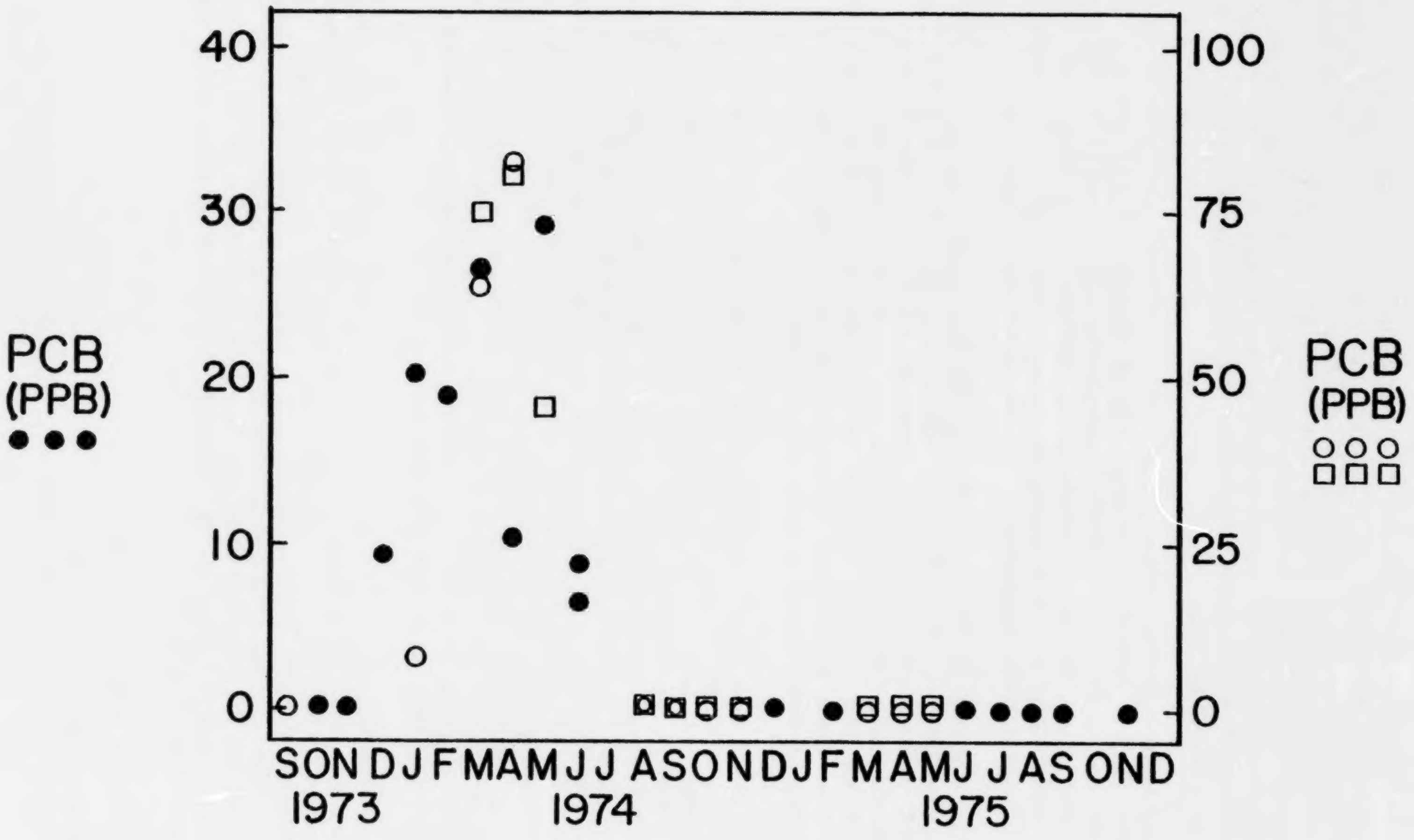


Figure 10. Temporal distribution of polychlorinated biphenyls in aquatic fauna in The Woodlands. ● ● mosquitofish (Gambusia sp.); □ □ Bluegill (Lepomis sp.); o o crayfish (Cambarus sp.).

The source of the PCBs in The Woodlands is not known. It is of interest that the peak of PCBs in all components of the ecosystem appeared during a period of intense cut and fill operations as well as utility installations. An abandoned land fill with disposed capacitors or other electronic materials could have affected the increase in concentration as could the use of road oil contaminated with PCBs. Neither of these possibilities were verified by observation.

Chlorinated Hydrocarbon Pesticides--

In the first year of investigation trace levels of DDE were observed in samples of crayfish, mosquito and bluegills obtained from The Woodlands aquatic ecosystem. After completion of The Woodlands Golf Course, the surface waters and soils in ponds and adjacent ditches were examined for halogenated compounds.

In the spring of 1975 Mirex, a chlorinated camphene, was detected in water, soil and some aquatic organisms (Figure 11). The highest values were found in mosquitofish and the lowest in water samples with the residues in soil being intermediate between the fish and water. If there was any biological amplification in the fish from this aquatic system it was limited to approximately a four-fold increase (Figure 11).

Water from the Conference Center Lakes (A and B) was used for irrigation of portions of the golf course. Since these manmade impoundments were the potential recipients of both irrigation and stormwater runoff, the lake water sediments and the mosquito fish were examined for Mirex. The results are shown in Figure 12. The highest level of pesticide was observed in mid- to late summer (1975) and thereafter concentration in all these components of the pond ecosystem diminished rapidly with the soil residues showing the slowest rate of decline. Mirex concentration in Lake Harrison was at least one order of magnitude lower than concentrations observed on The Woodlands Golf Course. The lower concentration due to lake water dilution by groundwater pumpage, runoff and treated wastewater.

During August of 1974 chlordane was also detected in the golf course study. Residues were found in soil, water and aquatic organisms (Figure 13). The highest levels of chlordane were found in the crayfish from golf course ponds. Somewhat less was observed in the same organisms from ditches adjacent to the course. Similar, although not as pronounced, results were observed in the concentration of chlordane in the waters from the same areas (Figure 13).

Bacteriological Enumerations

Surface Water Characteristics--

Bacterial counts during dry weather were determined in

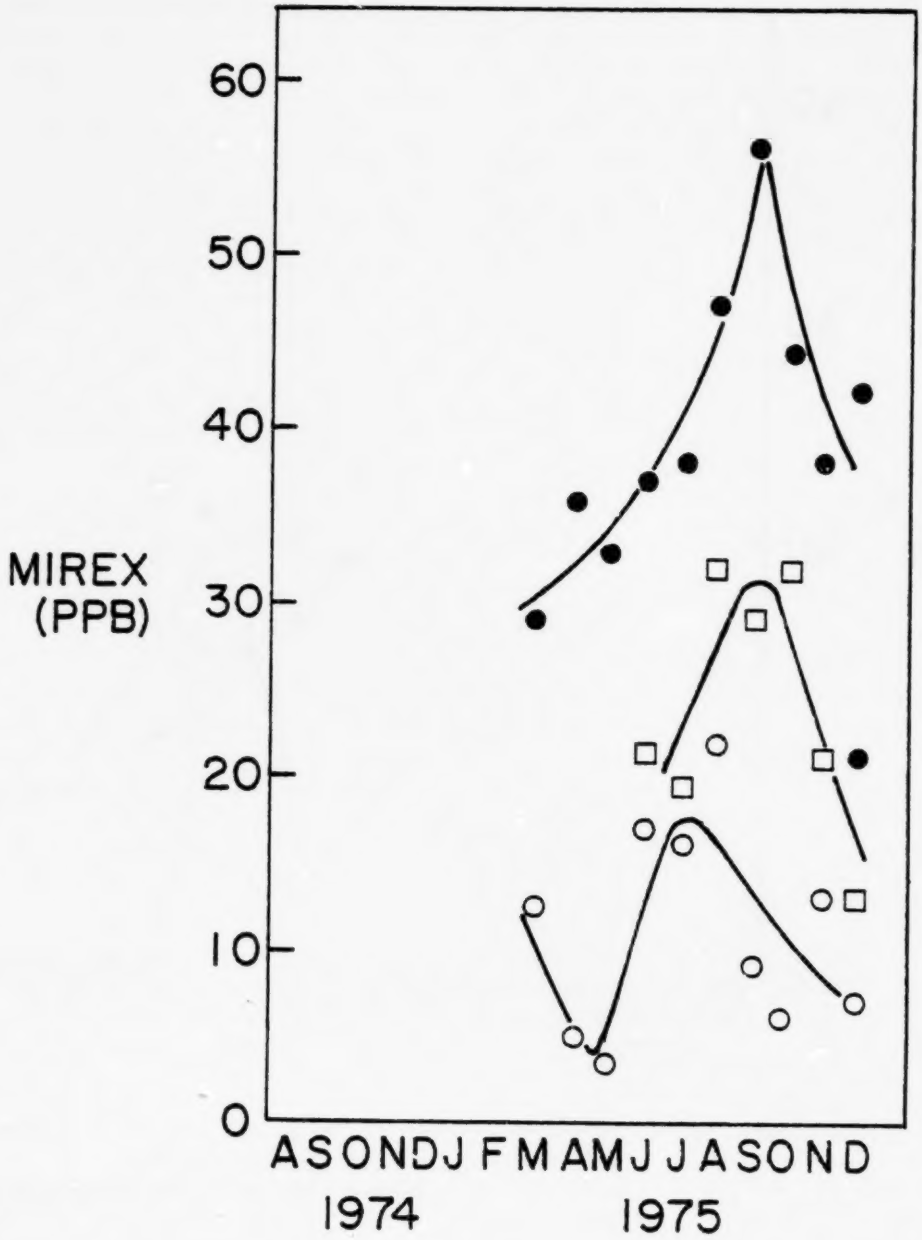


Figure 11. Temporal distribution of Mirex in The Woodlands gold course. ●-● mosquitofish (Gambusia sp.); □-□ soil; o-o water.

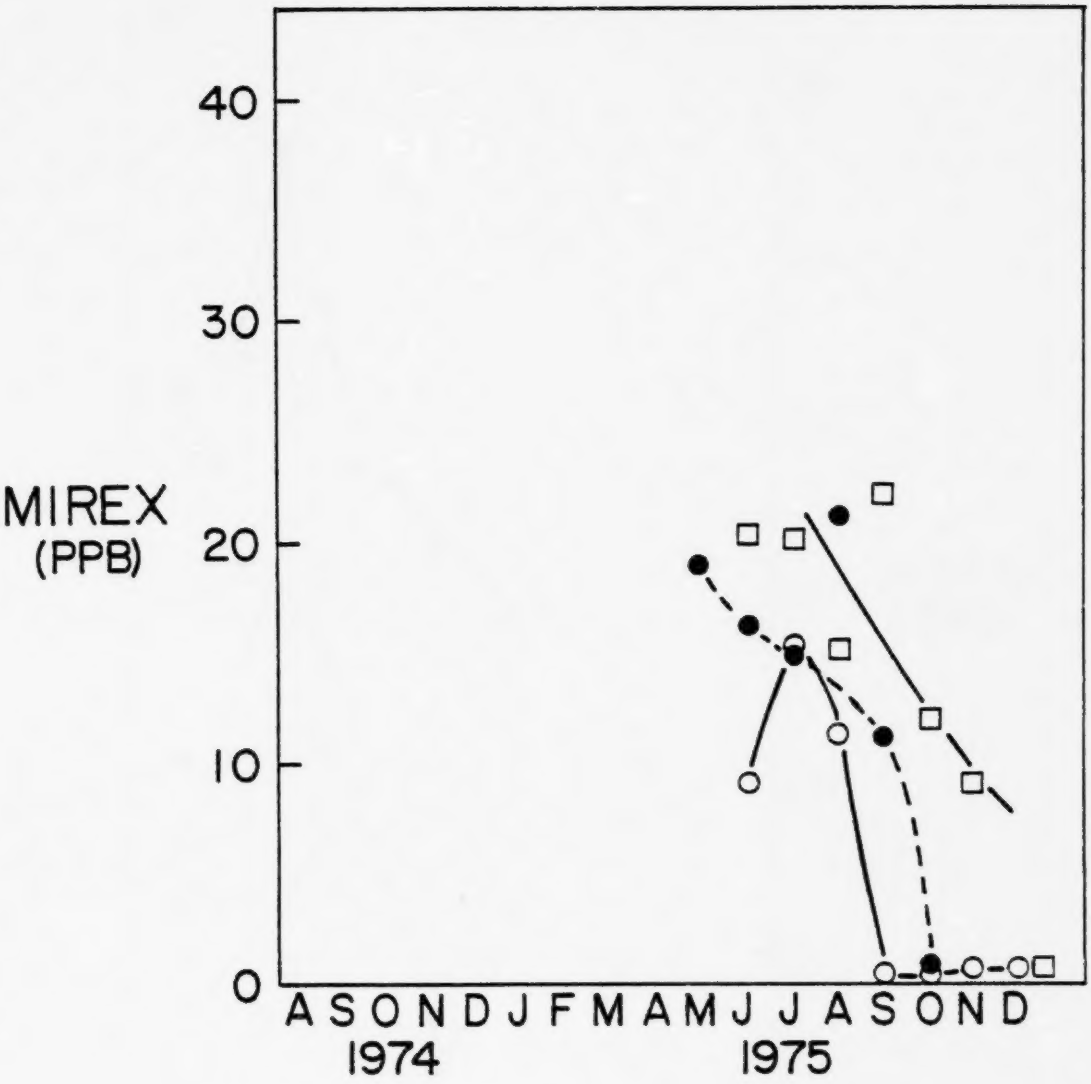


Figure 12. Temporal distribution of Mirex in the Conference Center Lakes (A&B). □-□ soils; ●-● mosquitofish (*Gambusia* sp.); o-o water.

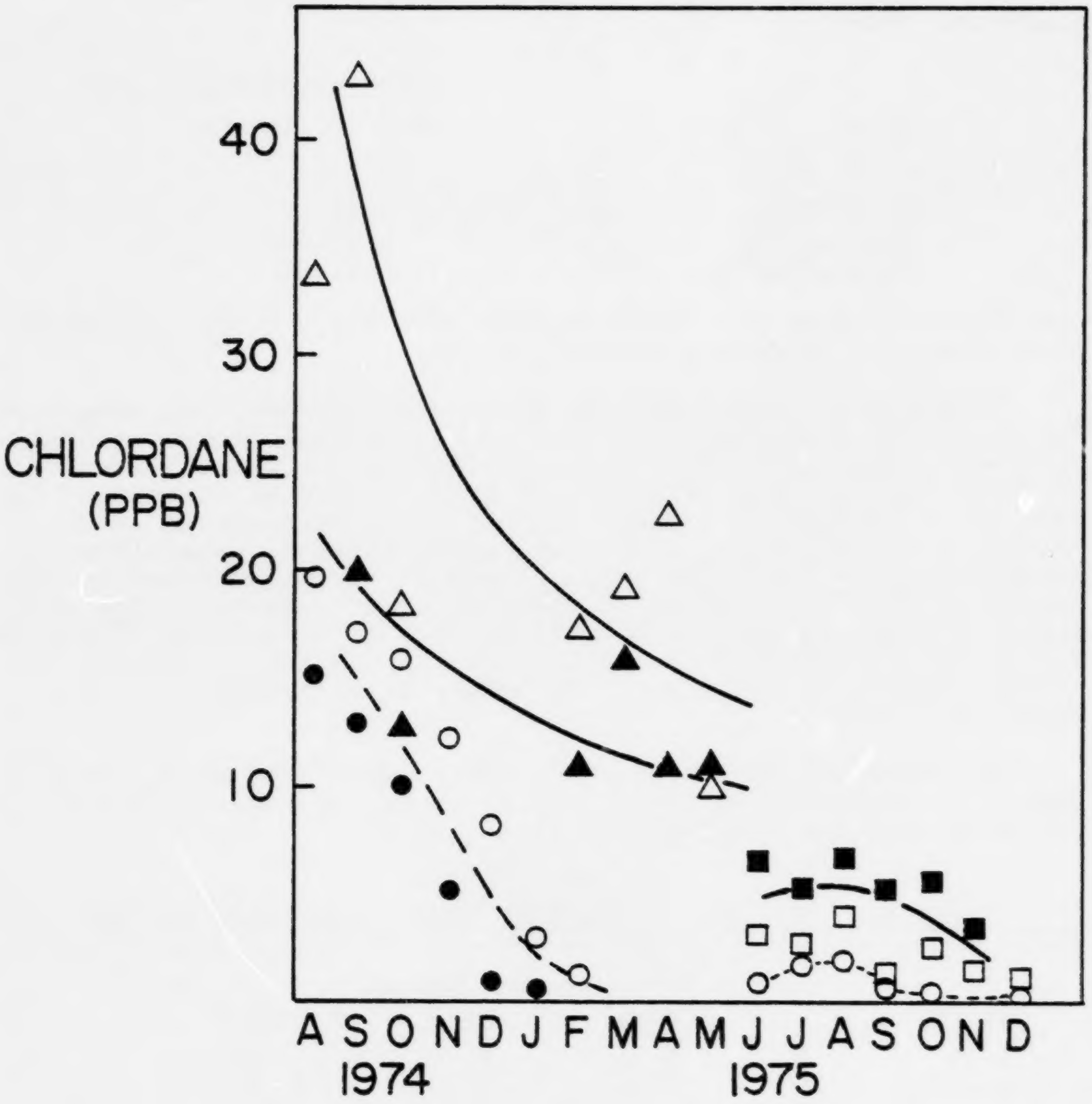


Figure 13. Temporal distribution of chlordane in The Woodlands gold course. Δ-Δ crayfish (*Cambarus* sp.)from pond; ▲-▲ crayfish (*Cambarus* sp.) from ditch; o-o pond water; ●-● ditch water; mosquitofish (*Gambusia* sp.) from pond; □-□ soil from pond.

Panther Branch. Indicator bacteria numbers varied widely as indicated below:

	Range (number/100 ml)
Total Coliform (TC)	200-10,000,000
Fecal Coliform (FC)	10-214,000
Fecal Streptococci (FS)	10-1,580
Pseudomonas aeruginosa (PS)	10-53,600
Staphylococcus sp. (ST)	1-23,400
Salmonella sp. (SA)	1-5,800

The maximum values are comparatively high for a rural, forested area receiving no direct sewage discharges.

Storm events monitored for water quality were also monitored for microbiological content. The range and mean bacterial counts observed during each storm event at The Woodlands are presented in Table 12. All bacterial counts are reported as logarithms to base 10. Substantial numbers of bacteria were observed in The Woodlands storm runoff, including runoff from the undeveloped watershed, site P-10. Pathogenic species were identified at all Woodlands monitoring sites in relatively high numbers. For example, *Salmonella sp.* were identified at a mean count of 77/100 ml for storm event #10 at site P-10. In the majority of events the maximum bacterial count occurred before or coincidental to the hydrograph crest.

A summary of the three storm events monitored at Westbury Square is presented in Table 11 (the storm event of 11/75 was not monitored for water quality).

TABLE 11. SUMMARY OF WESTBURY RUNOFF BACTERIAL QUALITY

		log No./100 ml		
Storm		Min.	Max.	Mean
5/75 (n=11)[1]	TC	4.70	8.70	7.48
	FC	3.86	4.60	4.34
	FS	2.60	4.61	4.12
	PS	2.30	4.40	3.88
	ST	3.07	4.30	3.91
	SA	<1.51	<1.51	<1.51
6/75 (n=12)	TC	4.47	8.70	7.48
	FC	2.93	4.60	4.34
	FS	2.83	4.61	4.12
	PS	2.97	4.40	3.88
	ST	3.43	4.30	3.91
	SA	<1.40	<1.51	<1.51

(continued)

TABLE 11 (continued)

		log No./100 ml		
Storm		Min.	Max.	Mean
11/75 (n=5)	TC	6.26	6.67	6.49
	FC	3.96	4.50	4.28
	FS	4.39	4.68	4.51
	PS	4.31	TNTC[2]	4.54
	ST	TNTC	TNTC	--
	SA	2.00	4.17	3.19

[1] Number of Samples [2] Too Numerous to Count

Stormwater bacterial counts at Westbury were generally greater than or equal to counts observed at The Woodlands. High sample variations were common for PS, ST and SA determinations. Generally, the concentrations of FC, TC and FS were highest toward the end of runoff, unlike The Woodlands stormwater.

Hunting Bayou stormwater was analyzed for TC only. Results, summarized below indicate TC concentrations were at high levels, ranging from 3.1 x 10^4 to 7 x 10^8/100 ml, throughout the runoff event. Geometric mean TC counts at Hunting Bayou were similar to the levels observed at The Woodlands, however maximum TC at Hunting Bayou was an order of magnitude greater.

	Total Coliform ($\log_{10}$ No/100 ml)			
Storm	Min.	Max.	Mean	No. of Samples
3/20/74	4.49	5.48	4.94	13
3/27/74	4.86	6.45	5.60	67
5/8/75	7.00	8.84	7.79	27
6/30/75	4.78	6.70	6.08	35

Algal Enumerations

Panther Branch Algal Populations--

Seventy-nine species of algae were identified from Panther Branch. Twenty-six species (32.9%) were identified from all sites along Panther Branch, 18 species (22.8%) were present at two collection sites, and 35 species (44.3%) were found at only one site. Thus, the algal populations along Panther Branch are not uniform in species composition, and collections from only one site would not be indicative of the total algal populations of the stream. A summary of the number of species identified and their taxonomic division is presented in Table 13.

TABLE 12. SUMMARY OF INDICATOR AND PATHOGEN BASE LEVELS, PEAK LEVELS AND MEAN LEVELS AT THE WOODLANDS

		Log of No./100 ml					Log of No./100 ml		
Station	Indicator	Min.	Max.	Mean	Station	Indicator	Min.	Max.	Mean
1/18/74	TC	3.95	5.37	4.92	12/5/74	TC	4.48	6.02	5.38
P-30	FC	2.75	4.32	3.63	P-30	FC	2.60	4.28	3.86
	FS	2.45	4.30	3.61		FS	2.00	4.24	3.48
	PS	--	--	--		PS	2.00	3.00	2.87
	ST	--	--	--		ST	2.90	3.80	3.45
	SA	--	--	--		SA	1.52	2.42	1.94
4/22/74	TC	6.00	7.76	7.15	12/5/74	TC	4.00	6.32	5.13
P-30	FC	2.20	4.13	3.89	P-10	FC	2.00	4.06	3.20
	FS	1.95	4.33	3.73		FS	2.00	3.46	2.65
	PS	2.78	4.42	--		PS	1.00	2.77	2.15
	ST	--	--	--		ST	<1.00	3.73	2.77
	SA	--	--	--		SA	<1.39	2.52	1.88
10/28/74	TC	4.78	6.90	5.98	3/4/75	TC	4.68	5.61	5.17
P-30	FC	2.00	4.65	3.63	P-30	FC	2.58	3.32	3.00
	FS	2.00	5.15	3.73		FS	2.85	4.03	3.37
	PS	2.30	4.45	3.46		PS	1.48	2.00	1.80
	ST	2.00	5.52	3.77		ST	2.99	4.16	3.40
	SA	1.70	3.40	--		SA	<1.40	1.40	<1.40

(continued)

TABLE 12 (continued)

		Log of No./100 ml					Log of No./100 ml		
Station	Indicator	Min.	Max.	Mean	Station	Indicator	Min.	Max.	Mean
3/4/75	TC	5.36	6.03	5.58	3/12/75	TC	4.30	6.57	5.93
Lake B	FC	1.60	3.90	3.38	P-10	FC	<1.00	3.44	2.93
	FS	3.46	4.38	4.21		FS	<1.00	3.39	2.87
	PS	2.67	3.83	3.39		PS	<1.00	2.69	1.55
	ST	3.67	4.45	4.12		ST	1.00	3.40	2.52
	SA	<1.40	<1.40	<1.40		SA	<1.40	2.10	1.53
3/4/75	TC	3.85	4.70	4.52	3/12/75	TC	4.60	6.75	6.18
Lake A	FC	<1.00	1.30	.85	Lake B	FC	<2.00	3.46	3.12
	FS	2.60	3.72	3.16		FS	<2.00	3.93	3.53
	PS	<1.00	2.43	1.52		PS	<2.00	3.58	2.73
	ST	1.00	2.74	2.14		ST	2.85	5.23	4.04
	SA	<1.40	<1.40	<1.40		SA	<1.40	2.24	1.25
3/12/75	TC	4.78	6.72	5.99	3/12/75	TC	4.00	5.49	4.91
P-30	FC	1.00	3.65	2.41	Lake A	FC	<1.00	2.15	1.44
	FS	1.00	3.92	2.49		FS	1.88	3.53	3.12
	PS	<1.00	1.85	1.58		PS	<1.00	1.95	.47
	ST	2.38	3.89	2.98		ST	1.00	1.95	1.50
	SA	<1.40	2.00	1.74		SA	<1.40	2.40	1.47

(continued)

TABLE 12 (continued)

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Station	Indicator	Log of No./100 ml Min.	Max.	Mean
4/7/75	TC	3.77	6.80	5.48	4/7/75	TC	4.00	5.62	5.06
P-30	FC	2.00	4.40	3.38	Lake A	FC	2.00	3.60	3.03
	FS	2.00	4.42	3.47		FS	2.00	4.06	3.50
	PS	<2.00	3.51	2.67		PS	<2.00	3.36	2.61
	ST	2.30	3.85	3.26		ST	2.30	3.36	3.29
	SA	<1.51	2.12	1.72		SA	<1.51	2.00	.35
4/7/75	TC	4.32	6.79	5.18	9/5/75	TC	6.44	6.70	6.58
P-10	FC	<2.00	4.40	3.36	P-30	FC	3.00	3.60	3.39
	FS	2.00	4.24	3.05		FS	4.59	5.47	5.12
	PS	<2.00	3.26	2.35		PS	3.00	4.46	3.72
	ST	2.30	3.45	2.88		ST	3.70	4.43	4.10
	SA	<1.51	2.36	1.89		SA	<1.00	<1.00	<1.00
4/7/75	TC	4.00	5.80	5.25	9/5/75	TC	3.90	5.18	4.30
Lake B	FC	2.00	4.39	3.37	P-10	FC	<1.00	2.78	2.41
	FS	2.00	4.40	3.23		FS	1.60	2.63	2.19
	PS	2.00	3.57	2.81		PS	<1.00	1.90	1.60
	ST	2.48	3.83	3.17		ST	1.00	2.23	1.69
	SA	<1.51	2.51	.28		SA	<1.00	1.00	1.00

(continued)

TABLE 12 (continued)

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Station	Indicator	Log of No./100 ml Min.	Max.	Mean
9/5/75	TC	6.34	6.86	6.55	10/25/75	TC	5.20	6.02	5.41
Lake B	FC	3.48	4.26	3.90	P-10	FC	2.60	4.81	3.48
	FS	4.41	4.99	4.74		FS	2.20	4.39	3.36
	PS	4.11	5.12	4.66		PS	1.47	3.97	2.99
	ST	3.78	5.03	4.42		ST	2.04	3.43	2.68
	SA	<1.00	<1.00	<1.00		SA	<1.40	2.17	1.54
9/5/75	TC	3.78	4.97	4.28	10/25/75	TC	4.90	6.87	6.01
Lake A	FC	2.00	2.85	2.36	Lake B	FC	3.20	4.44	4.22
	FS	2.04	2.88	2.52		FS	3.30	4.85	4.16
	PS	1.46	3.40	2.62		PS	2.60	4.63	3.62
	ST	1.50	2.82	2.05		ST	2.47	5.02	4.03
	SA	<1.00	<1.00	<1.00		SA	<1.40	2.30	1.40
10/25/75	TC	4.00	6.04	5.52	10/25/75	TC	3.84	4.99	4.20
P-30	FC	3.17	4.62	4.17	Lake A	FC	1.00	3.00	2.41
	FS	3.14	4.94	4.26		FS	1.69	3.21	2.88
	PS	3.11	4.77	4.34		PS	1.00	3.66	2.04
	ST	2.77	5.05	3.72		ST	1.00	3.06	2.29
	SA	<1.40	2.17	1.62		SA	<1.40	2.30	.62

(continued)

TABLE 12 (continued)

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Station	Indicator	Log of No./100 ml Min.	Max.	Mean
3/7/75	TC	5.30	5.92	--	3/7/76	TC	4.30	5.18	--
Lake B	FC	3.04	4.80	--	P-30	FC	2.78	3.53	--
	FS	3.23	3.79	--		FS	3.18	3.72	--
	PS	2.30	3.04	--		PS	3.15	3.41	--
	ST	3.70	4.41	--		ST	2.36	3.04	--
	SA	<2.00	2.70	--		SA	<1.00	<1.00	--
3/7/76	TC	3.60	4.04	--	3/9/76	TC	4.36	5.11	--
Lake A	FC	1.48	1.95	--	Lake B	FC	2.78	3.91	--
	FS	2.04	2.34	--		FS	2.78	3.83	--
	PS	<1.00	1.70	--		PS	<1.00	1.95	--
	ST	2.32	3.28	--		ST	2.28	4.50	--
	SA	<1.00	<1.00	--		SA	<2.00	<2.00	--
3/7/76	TC	4.20	4.88	--	3/9/76	TC	3.63	4.43	--
P-10	FC	2.64	3.77	--	Lake A	FC	2.20	2.47	--
	FS	2.70	3.40	--		FS	2.28	2.86	--
	PS	<1.00	2.45	--		PS	<1.00	1.70	--
	ST	2.45	3.15	--		ST	2.70	3.28	--
	SA	<2.00	2.30	--		SA	<1.00	<1.00	--

(continued)

TABLE 12 (continued)

		Log of No./100 ml					Log of No./100 ml		
Station	Indicator	Min.	Max.	Mean	Station	Indicator	Min.	Max.	Mean
3/9/76	TC	4.08	4.96	--	4/5/76	TC	4.81	6.51	- -
P-30	FC	3.20	3.86	--	Lake B	FC	2.90	3.78	--
	FS	3.56	4.03	--		FS	2.49	3.11	--
	PS	1.00	2.11	--		PS	<2.00	2.70	--
	ST	3.95	4.48	--		ST	3.45	4.45	--
	SA	<2.00	<2.00	--		SA	<2.00	2.00	--
4/5/76	TC	3.72	4.26	--	4/5/76	TC	3.76	3.97	--
P-10	FC	1.90	2.50	--	Lake A	FC	1.48	2.79	--
	FS	2.30	2.76	--		FS	2.69	3.09	--
	PS	<2.00	2.30	--		PS	1.00	1.90	--
	ST	1.48	2.28	--		ST	2.00	2.89	--
	SA	<1.00	1.00	--		SA	<1.00	<1.00	--
4/5/76	TC	3.00	5.77	--					
P-30	FC	<2.00	4.00	--					
	FS	<2.00	4.59	--					
	PS	<2.00	3.00	--					
	ST	2.00	4.59	--					
	SA	<2.00	2.30	--					

TABLE 13. SUMMARY OF PANTHER BRANCH AQUATIC ALGAE

Division		Number of Species Identified in Panther Branch
Chlorophyta	92[a]	43
Cyanophyta	15	8
Chrysophyta	16	12
Euglenophyta	1	15
Pyrrophyta	1	1
		79 Total number

[a] number of taxonomic species/division

Standing crops of algae at site P-10 and P-30 are presented in Figures 14 and 15, respectively. On a seasonal basis, algal cell numbers fluctuated more at site P-30 than at P-10. The algal standing crops at both sites were dominated primarily by members of the euglenoids (Euglenophyta), and green algae (Chlorophyta) were minor components of the total algal populations. Numbers of blue-green algae (Cyanophyta) were comparatively low at both sites, even though they were more numerous at site P-30. A survey of various collection sites along Panther Branch (May, 1974) also indicated that standing crops in this stream were dominated by euglenoids and/or diatoms (Chrysophyta), while numbers of green algae and blue-green algae were comparatively low. Dominance of this type is indicative of slightly acid streams with high organic carbon content.

Soil Algae--

Fifty-two genera of algae were identified in soils collected from disturbed and undisturbed sites in The Woodlands (see Table 14). Undisturbed soils had larger algal species diversities and fewer algal numbers than disturbed soils. Green algae (Chlorophyta) genera were most numerous in soils from the forest, while disturbance of soils favored the development of a more diverse blue-green (Cyanophyta) flora and inhibited green algae diversity.

The change in algae characteristics is probably a result of increases in soil pH and nutrient content which accompanied soil disturbance and fertilization. Undisturbed soils had the lowest pH (6.1), compared to high pH values of 6.7 to 7.8 in disturbed soils. The results confirm floristic surveys in other regions of the United States which show that alkaline soils favor the development of more luxuriant blue-green algal flora than do acid soils (41, 42, 43). Higher algal numbers in disturbed soils corresponded to the greater concentrations of nitrogen and phos-

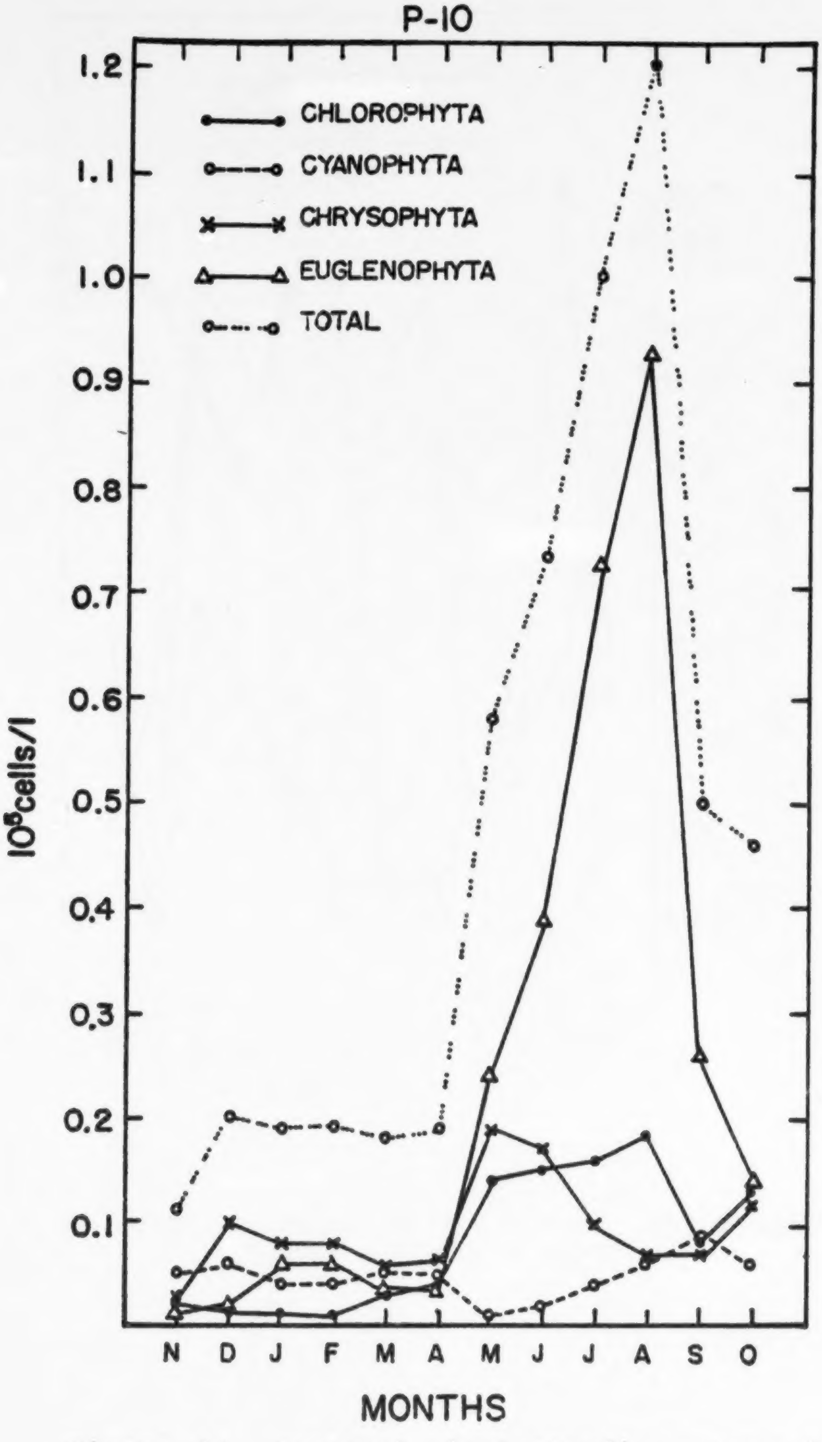


Figure 14. Seasonal algal standing crops at P-10 in Panther Branch.

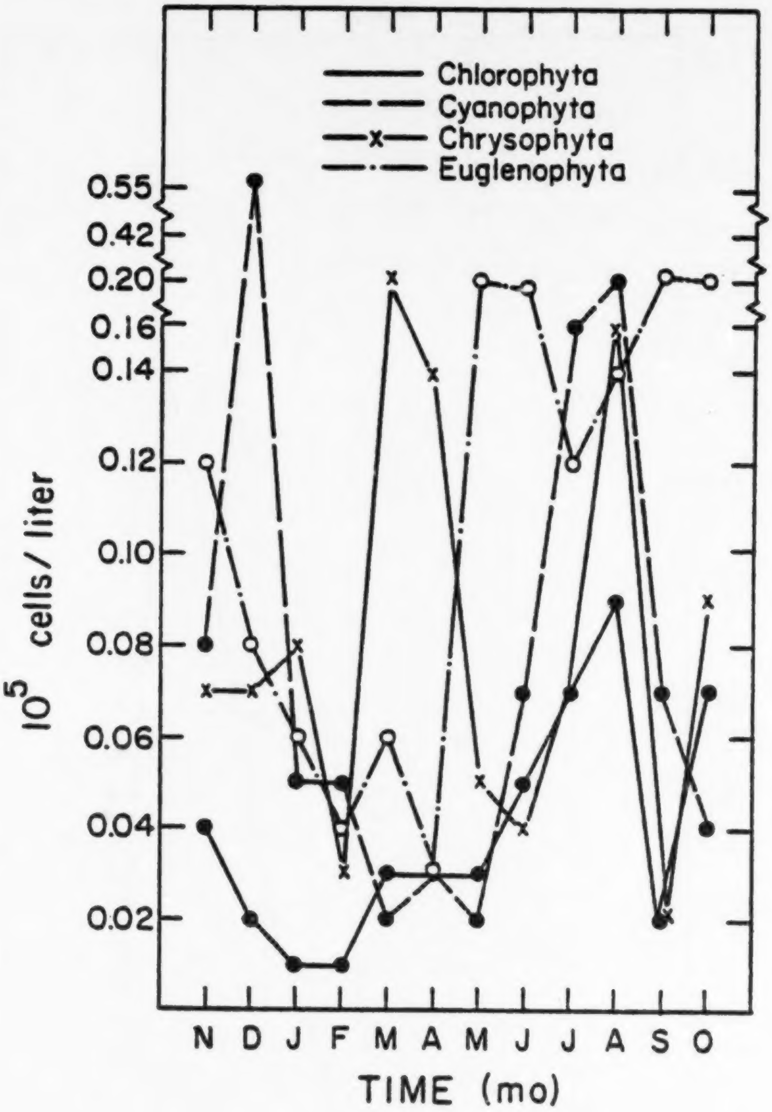


Figure 15. Seasonal algal standing crops at P-30 in Panther Branch.

phorus found in these soils. The increase in soil nutrient concentration is due primarily to fertilization.

TABLE 14. SUMMARY OF EDAPHIC ALGAE IN THE WOODLANDS

Division	Undisturbed Forest Soil	Disturbed Soils Golf Course	Lawn
Chlorophyta	27[a]	7	4
	3853[b]	39629	17400
Cyanophyta		4	4
	586	1446	7195
Chrysophyta	11	4	3
	1297	13084	12790
Euglenophyta	3	1	--
	--	--	--
Total	46	16	11
	5736	54159	37385

[a] numbers of genera identified (species were not determined)

[b] number of cells/g of soil

Since terrestrial and aquatic ecosystems are connected hydrologically, they cannot be considered as totally disjuncted units. Surface drainage serves as a major component in this hydrologic linkage and is thus an important ecological parameter. Land usage in a watershed can determine the quality, as well as the quantity, of surface runoff, thus influencing aquatic habitats in the watershed. In addition to providing potential nutrients for algal growth, surface drainage probably transports algal cells to aquatic habitats from surrounding soils. Since land use affects edaphic algal populations, it must also influence the diversity of algae which could be transported by surface runoff. For example, a more diverse assemblage of blue-green algae could potentially enter lakes in the study area by surface drainage from disturbed, rather than undisturbed, soils.

Stormwater Comparison with Sewage

Table 15 compares stormwater runoff and sanitary wastewater quality. Stormwater constituents are lower than raw sewage with the exception of suspended solids in runoff from Hunting Bayou and The

TABLE 15. WATER QUALITY FOR STORMWATER RUNOFF, UNTREATED SEWAGE, AND TREATED SEWAGE (ALL UNITS IN mg/l)

STORMWATER RUNOFF[1]	Total Suspended Solids	Total Kjeldahl Nitrogen	Total Phosphorous	Total Chemical Oxygen Demand
Forest (P-10)	6.5 - 67	0.10 - 1.61	0.03 - 0.09	43 - 63
Forest, Under Development (P-30)	109 - 321	0.06 - 1.41	0.13 - 0.30	40 - 51
Lake B	283 - 2877	1.79 - 4.14	0.11 - 0.53	49 - 123
Lake A	24 - 245	0.17 - 1.31	0.05 - 0.14	38 - 47
Hunting Bayou	71 - 207	1.56 - 3.94	0.41 - 1.28	77 - 179
Westbury Square	24 - 70	1.48 - 2.19	0.73 - 1.14	39 - 54
SEWAGE				
Untreated[1]	200	40	10	350
Secondary Treatment	20	30	10	40
Advanced Treatment[2]	5	10	1	15

---

[1] Range of flow-weighted mean concentrations for number of storm events monitored.

[2] The Woodlands Water Reclamation Plant - Design Efficiency

Woodlands developing areas. Advanced wastewater treatment yields lower COD and TSS values than stormwater, however nutrients remain higher. As a result, sophisticated nutrient removal processes would be necessary to achieve low concentrations observed in stormwater runoff.

Ten samples of untreated and chlorinated secondary wastewater effluent were obtained from two large, well-operated sewage plants in Houston for bacteriological examination. The data obtained is compared to the bacteriological quality of stormwater runoff in Table 16. Bacterial numbers were lowest in chlorinated effluent, higher in runoff and highest in untreated wastewater. Urban runoff contained higher numbers than forest runoff.

OBSERVED TEMPORAL AND SPATIAL VARIATIONS IN STORMWATER RUNOFF QUALITY

Pollutograph Analysis

A pollutograph is defined as a plot of pollutant concentration versus time. In this sub-section it is plotted for stormflow quality. Temporal changes of water quality during runoff events are important to the understanding of the impact of these non-point sources on stream quality. The time-concentration relationship is also critical in consideration of stormwater treatment alternatives. Pollutographs observed during the study exhibited the five generalized patterns shown in Figure 16. These concentration patterns were common to all watersheds, although levels of a particular parameter were site dependent.

Specific conductance of groundwater which feeds streamflow is high due to dissolved minerals and as a result stormwater inflow decreases stream conductance similar to the second pollutograph shown in Figure 16.2. This dilution pattern applies to other streamwater constituents, including some found in wastewater effluents, which are concentrated in dry-weather flow. The concentrations of SOC, soluble COD and total COD often increased as runoff progressed, with highest concentrations observed at the end of the runoff (Figure 16.4). Streamflow contributions from interstitial and bank storage flow is greatest late in runoff and could account for the pattern if enriched by contact with soils serving as an organic carbon source. DO concentrations in stormwater increased proportional to flow and assumed a hydrograph-shaped pollutograph (Figure 16.5). Increased reaeration at greater streamflows accounts for this phenomena. Several parameters observed at site P-10 remained at a constant level throughout the hydrograph, including pH, NH_3, NO_2 and soluble COD (Figure 16.3). This pattern was not commonly observed at the other watersheds where land use is diversified.

TABLE 16. COMPARISON OF STORMWATER AND WASTEWATER MICROBIOLOGICAL ANALYSIS (NUMBERS/100 ml)

	The Woodlands Runoff Storm Event 10				Storm Event 11				Municipal[1] Wastewater	
	P-10		P-30		Hunting Bayou[4]		Westbury[5]			
	Avg. Count[2]	Max. Count	Avg. Count[3]	Max. Count	Avg. Count	Max. Count	Avg. Count	Max. Count	Untreated	Clor-inated 2ndary trtd
Total Coliform	1.51×10^5	6.3×10^6	3.02×10^5	6.6×10^6	1.33×10^8	7.0×10^8	1.57×10^8	5.03×10^8	4.12×10^8	246
Fecal Coliform	2.34×10^3	7.8×10^4	2.4×10^3	2.5×10^4	---	---	2.56×10^4	5.7×10^4	3.00×10^7	18
Fecal Streptococci	1.12×10^3	1.7×10^4	3.09×10^3	2.69×10^4	---	---	2.53×10^4	4.1×10^4	1.88×10^6	6.7
Pseudomonas sp.	224	1.8×10^3	468	3.3×10^3	---	---	1.58×10^4	2.5×10^4		
Staphylococcus sp.	760	2.8×10^3	1.82×10^3	7.8×10^3	---	---	1.15×10^4	2.0×10^4		
Salmonella sp.	78	230	52	132	---	---	Not Found	Not Found		

1. Averaged from 14 samples, collected from Houston sewage treatment plants.
2. Averaged from 34 samples.
3. Averaged from 27 samples.
4. Averaged from 27 samples.
5. Averaged from 11 samples.

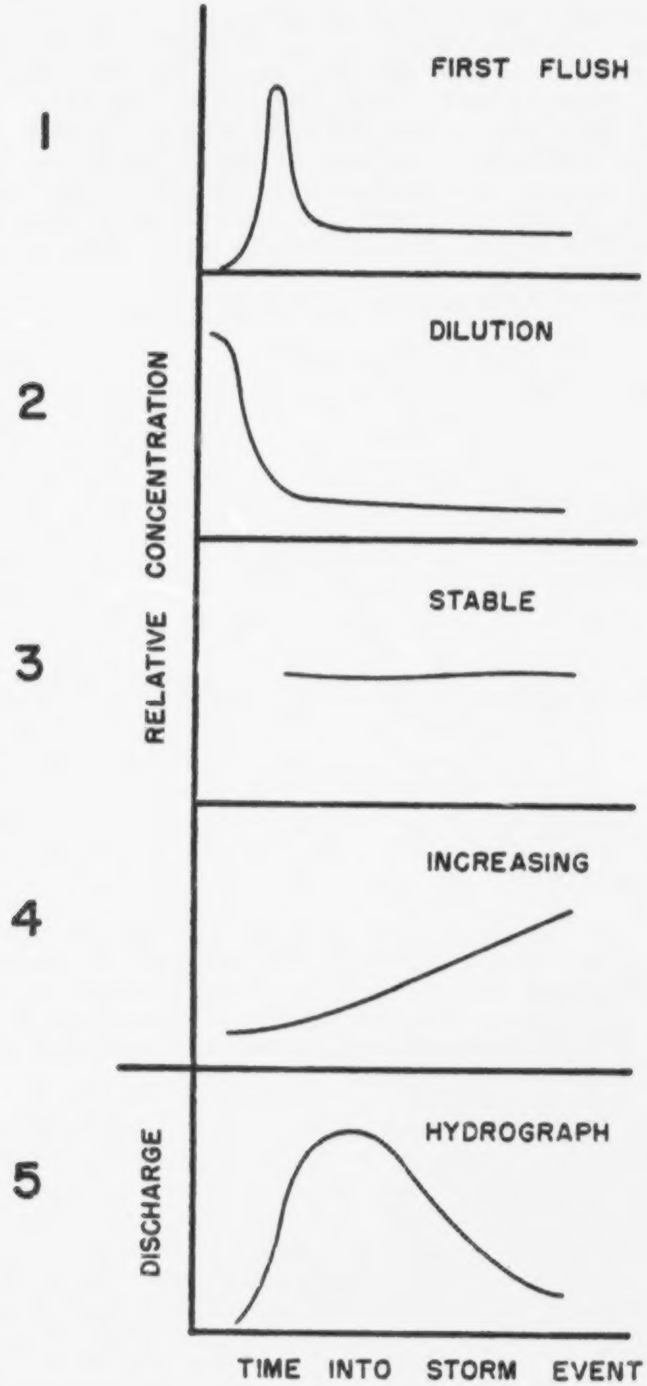


Figure 16. Generalized pollutographs observed for stormwater parameters.

The "first flush" pollutograph pattern is characterized by an abrupt rise in concentration early in the runoff event. At Hunting Bayou, the "first flush" was observed for the greatest number of runoff constituents including TSS, turbidity, ortho P, TKN, TP, NH_3, NO_2 and NO_3. The Hunting Bayou watershed has a fraction of impervious surface area and includes a diverse land use mix including industrial and commercial activities. Turbidity and TSS parameters exhibited the highest peak values over baseline, while peak values for other constituents were less pronounced.

Effect of Land Use on Stormwater Runoff Quality

Pollutant Load-Runoff Relationships--

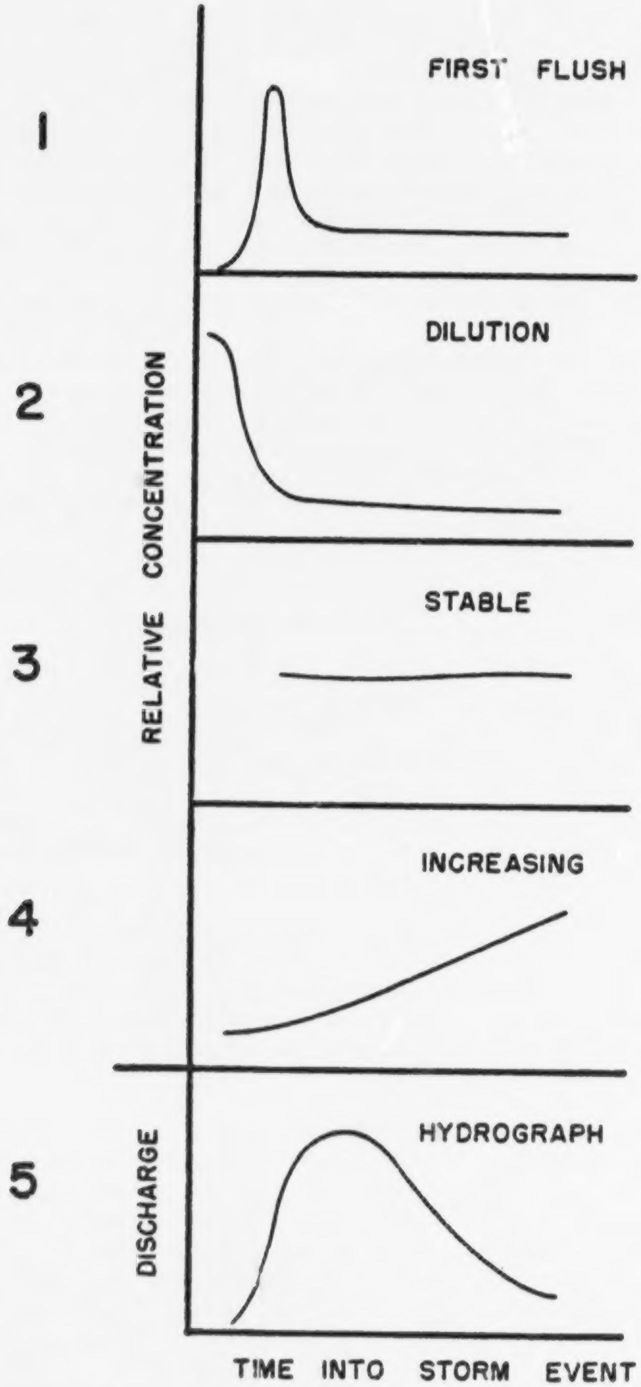
Total pollutant loads were plotted against total runoff of each storm event and regression lines were fitted to correspond to Hunting Bayou, Westbury, P-10 and P-30 watersheds. Fitted lines and associated correlation coefficients are shown in Figures 17-20 for the constituents TSS, total COD, TKN, TP, NO_3, NH_3, soluble COD and SOC. Correlation coefficients for a majority of the parameters were greater than $r = 0.8$ (r = correlation coeff.), however, three cases showed fair to poor correlation; P-30, NO_3 ($r = 0.775$), Westbury, NH3 ($r = 0.397$), and Hunting Bayou, SOC ($r = 0.161$).

NO_3, NH_3, TKN and TP relationships, shown in Figures 17-18, indicated that the urban watersheds produce nutrient loads greater than the forested watersheds. In all cases Hunting Bayou nutrient loadings are highest, followed in order by Westbury, P-30 and P-10.

TSS loads are highest in P-30 as a result of construction activities in the watershed and urban runoff solids loading is greater than forest runoff (Figure 19).

Runoff loads for nonspecific parameters (total COD, soluble COD and SOC are shown in Figures 19-20) are higher in forested watersheds than urban watersheds, with the exception of high total COD loads from Hunting Bayou. The data suggest organic material in runoff decreases with urbanization, however, insoluble pollutants, sediments and oils will increase.

A ranking of the four watersheds, on a lb/ac/in of runoff basis, illustrates the relative conditions for each site and pollutant. Table 17 shows these rankings for mean regression values at one inch (2.54 cm) of runoff for all parameters and sites. Confidence intervals (95%) are included in Table 17 to indicate significant differences in pollutant loads at one inch (2.54 cm) runoff. Confidence limits for Westbury show a particularly large spread due to the small number (2) of storms monitored for that watershed. Significant differences for the total COD, soluble COD and SOC cases are indicated, with some overlap in the TSS case. The patterns of nutrient response for the urban developing and forested watersheds is distinctive, with the urban response producing loads up to an order of magnitude larger. Hunting Bayou ranks as the producer of the largest pollutant loads.



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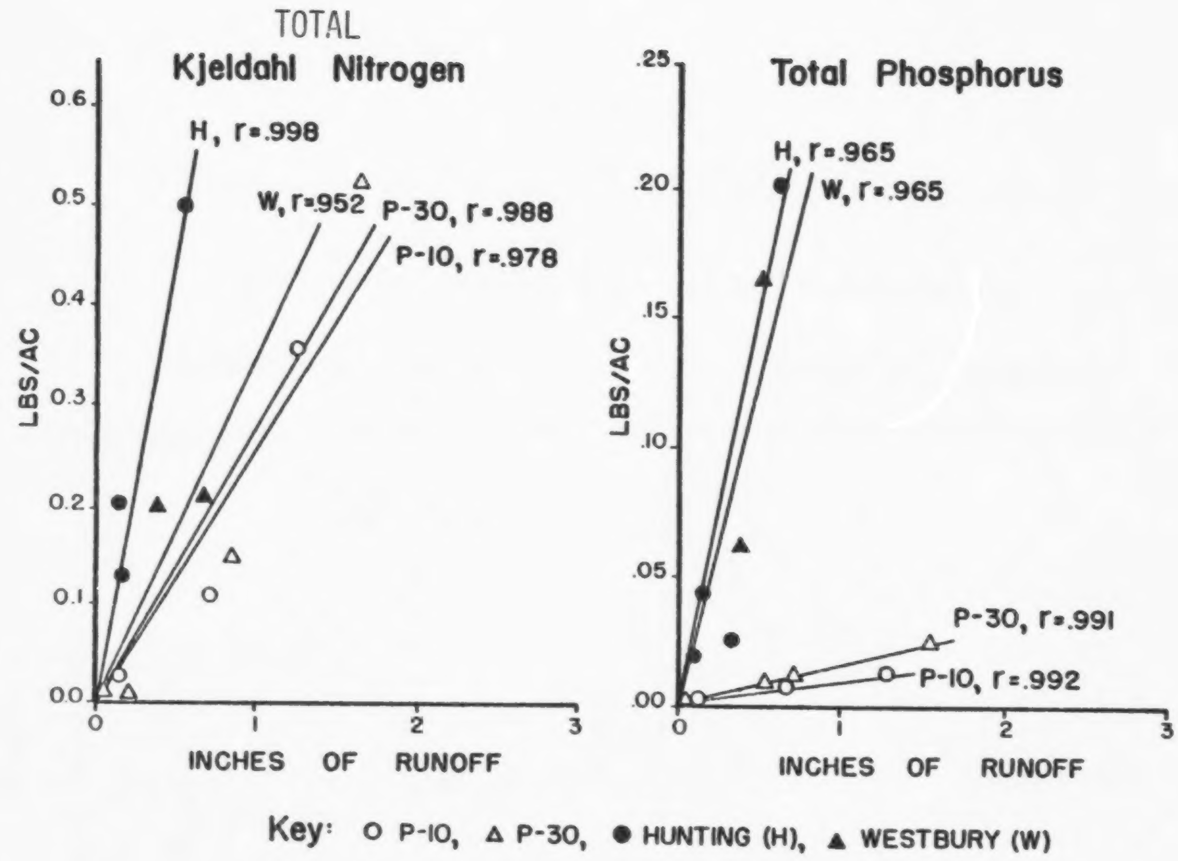


Figure 17. Load-runoff relationships for TKN and TP. (r = correlation coefficient)

$\frac{\text{lbs}}{\text{ac}}$ x 1.84 = kg/ha

1 in = 2.54 cm

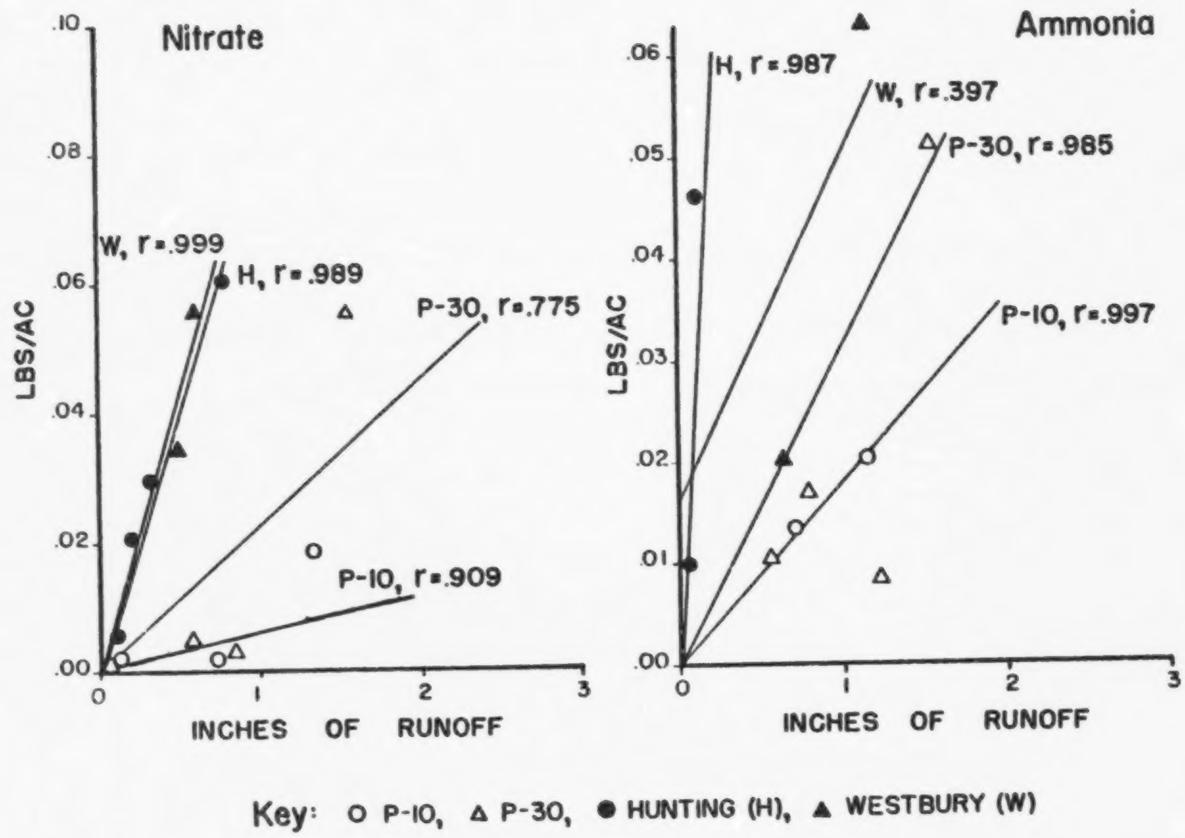


Figure 18. Load-runoff relationships for NO_3 and NH_3. (r = correlation coefficient)

$\frac{lbs}{ac}$ x .184 = kg/ha

1 in = 2.54 cm

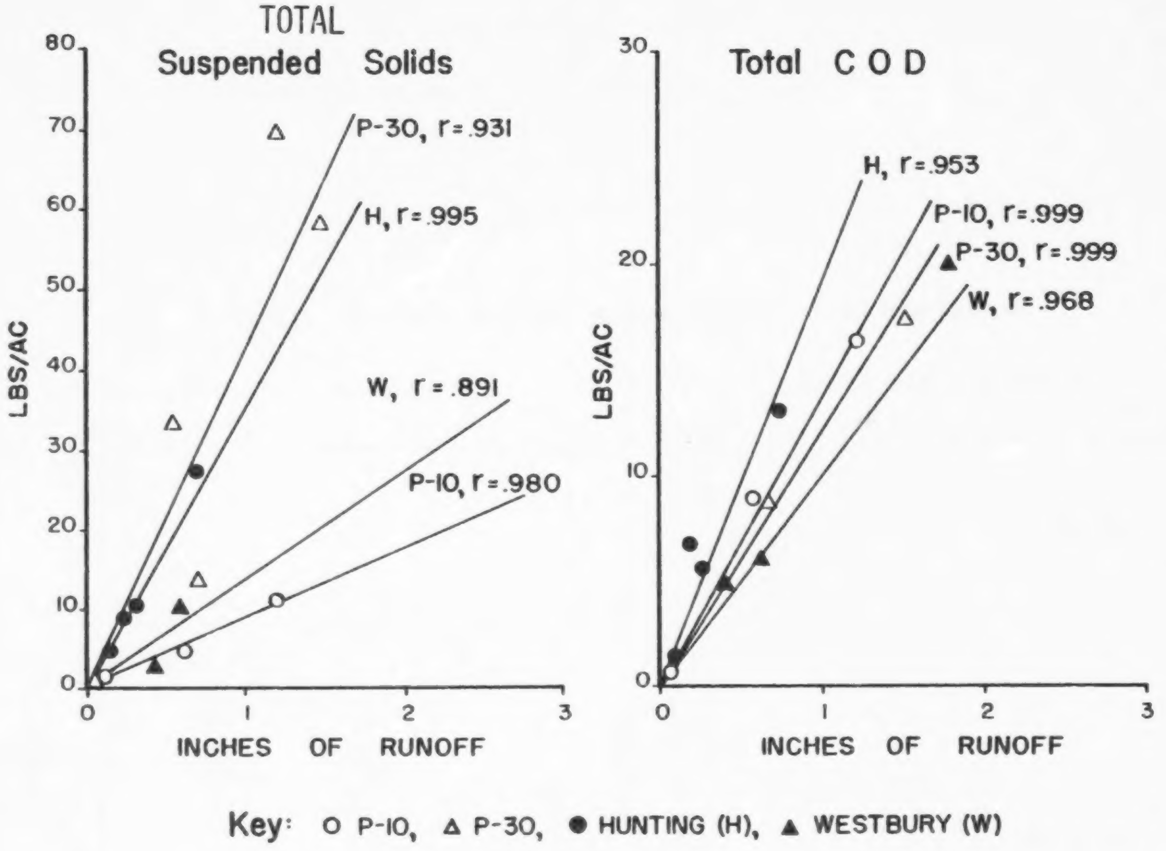


Figure 19. Load-runoff relationships for TSS and total COD as related to the watersheds studied. (r = correlation coefficient)

1 in. = 2.54 cm

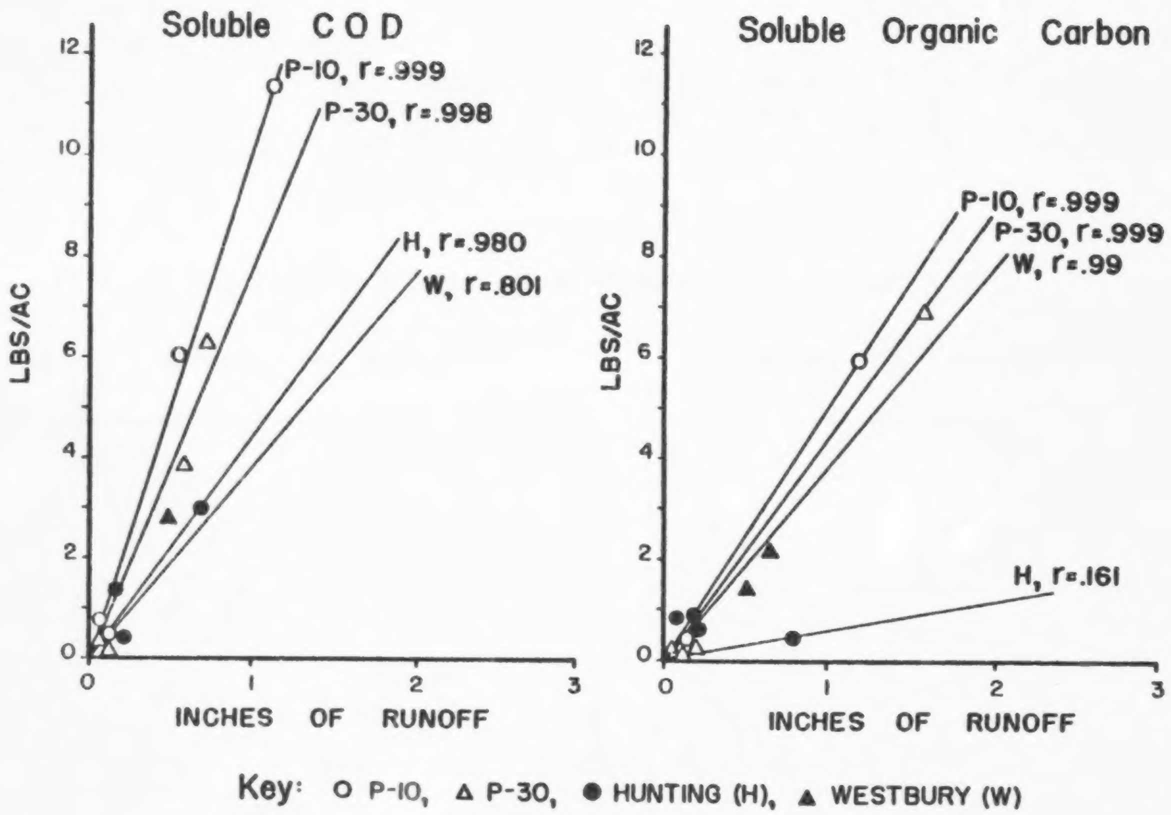


Figure 20. Load-runoff relationships for soluble COD and SOC. (r = correlation coefficient)

1 in = 2.54 cm

1 lb/ac = 1.12 kg/ha

TABLE 17. POLLUTANT LOAD RANKING OF THE FOUR STUDY AREA WATERSHEDS

		RANK			
		1	2	3	4
SS	Area	P30	HB	WB	P10
	Upper CL*	61.59	42.30	88.02	10.16
	1" Value	43.48	37.73	13.66	8.19
	Lower CL	25.36	33.15	-60.70	6.21
TCOD	Area	HB	P10	P30	WB
	Upper Cl	25.62	14.13	12.72	33.13
	1" Value	18.88	13.50	12.09	9.48
	Lower CL	12.14	12.87	11.46	-14.17
SCOD	Area	P10	P30	HB	WB
	Upper CL	10.01	9.27	6.64	31.56
	1" Value	9.86	8.76	4.44	4.06
	Lower CL	9.70	8.25	2.24	-23.45
SOC	Area	P10	P30	WB	HB
	Upper CL	5.045	4.78	4.48	2.64
	1" Value	5.00	4.54	3.75	0.70
	Lower CL	4.95	4.30	2.66	-1.25
NO_3	Area	WB	HB	P30	P10
	Upper CL	0.12	0.10	0.038	0.020
	1" Value	0.088	0.087	0.020	0.012
	Lower CL	0.057	0.072	0.0031	0.0051
NH_3	Area	HB	WB	P30	P10
	Upper CL	0.58	1.28	0.037	0.020
	1" Value	0.48	0.069	0.031	0.018
	Lower CL	0.38	-1.14	0.025	0.016
TKN	Area	HB	WB	P30	P10
	Upper CL	1.049	1.50	0.36	0.38
	1" Value	0.95	0.40	0.30	0.28
	Lower CL	0.85	-0.76	0.24	0.18
TP	Area	HB	WB	P30	P10
	Upper CL	0.40	0.90	0.028	0.017
	1" Value	0.28	0.24	0.021	0.014
	Lower CL	0.16	-0.43	0.014	0.011

* 95% Confidence Level. All confidence levels are for mean regression values at 1 inch (2.54 cm) of runoff. All loads are in lb/ac.

P30 = Woodlands P30 Watershed
P10 = Woodlands P10 Watershed
HB = Hunting Bayou Watershed
WB = Westbury Watershed

Note: inch x 2.54 = cm, lb/ac x .184 = kg/ha

The load-runoff relations developed from several storm events can be extended in a useful way to estimate total annual loads for selected pollutants. A measured or predicted annual streamflow hydrograph is required along with average low-flow concentration values. During storm events, the load-runoff relation is used to predict the mass flow, while during intermittent low flows, mass flow is estimated by the product of streamflow and concentration.

A comparison of annual loads for TSS, TP, NO_3 and total COD is shown in Table 18 for the P-10 forested site and P-30 urbanizing site at The Woodlands. The developed load-runoff relations were used to calculate the storm generated mass flows. The urbanizing watershed appears to be contributing greater loads of TSS on an annual basis compared to the forested site.

The procedure allows direct comparison of storm generated pollutant loads from non-point sources with the low-flow contributions, which are primarily of natural background or point source origin. Consequently, non-point loads can be quantitatively determined as a function of land use patterns as more storm data becomes available from other urbanizing watersheds.

The annual load calculation can be used in conjunction with the U.S. Geological Survey grab sample method to calculate annual sediment loads. Relative accuracy of the two techniques remains undetermined.

Effects of Land Development on Runoff Quality--

Storm event #10--Stormwater quality monitored at site P-10 represents runoff from a forested, undeveloped watershed and accordingly serves as a baseline for assessing changes due to urbanization. The P-30 sampling site, located 6.8 miles (11 km) below P-10, monitors runoff from 5,500 acreas (2250 ha), in addition to the area monitored by the P-10 site. The additonal area includes construction activity of The Woodlands Developed Corporation. A comparison of these two sites during storm event #10 illustrates the effects of construction activity on runoff quality.

Heavy rainfall over the Panther Branch watershed on April 8, 1975 produced large amounts of runoff sampled at P-10 and P-30. Precipitation associated with the storm event began shortly after midnight on April 8, 1975 and continued till noon the same day. The storm featured 3 periods of intense rainfall at 4:30, 8:30 and 10:00 A.M. with interposing pauses of drizzle. The area rain gages measured 2.00, 2.65, 3.42 and 3.97 in. (5.08, 6.73, 8.64 and 10.1 cm) of rainfall, upper to lower watershed gages, respectively, with the Thiessen adjusted rainfall calculated to be 2.43 in. (6.17 cm) on the P-10 watershed, and 2.76 in. (7.01 cm) on the P-30 watershed. Average rainfall intensity was 0.76 in/hr (1.83 cm/hr) and antecedent soil moisture conditions were dry with no rain recorded 7 days prior to the storm and 2.5 in. (6.35 cm) the preceding month. Watershed runoff began after midnight April 8.

TABLE 18 ANNUAL MASS LOADS from P-10 and P-30 WATERSHEDS (OCTOBER 1974-SEPTEMBER 1975)

	P-10 Watershed				P-10 and P-30 Watersheds Combined				
Month	TSS lb × 10^5	TP lb × 10^2	NO_3 lb × 10^2	COD lb × 10^4	TSS lb × 10^5	TP lb × 10^2	NO_3 lb × 10^2	COD lb × 10^4	No. Storms
Oct. '74	0.433	0.80	0.96	8.85	6.18	2.32	1.92	18.8	1
Nov.	6.27	6.84	7.71	88.89	43.56	15.66	15.92	123.5	4
Dec.	3.71	4.16	4.42	54.46	26.84	12.02	8.79	81.1	4
Jan.	1.12	1.32	2.14	47.38	5.26	5.04	2.40	21.1	4
Feb.	2.18	2.61	5.21	30.71	17.22	6.50	5.70	55.0	1
Mar.	1.05	2.65	1.68	13.20	6.84	3.92	2.45	18.8	2
Apr.	4.42	7.54	7.78	65.67	37.40	14.16	12.10	117.8	3
May	1.42	1.66	2.46	29.18	8.00	4.12	4.81	27.8	4
June	0.59	2.59	8.21	5.68	1.06	1.40	0.62	6.1	2
July	0.17	0.14	0.23	3.25	0.46	1.30	0.37	3.9	0
Aug.	0.08	0.065	0.068	1.50	0.26	0.77	0.21	2.2	0
Sept. '75	0.01	0.005	0.006	0.13	0.027	0.08	0.022	0.2	0
Total Load	21.50	30.38	40.87	348.91	154.10	67.35	55.37	476.3	25
	P-10 Watershed				P-30 Less P-10 Watershed				
Total Load (lbs/ac)	134	0.189	0.255	217	2387	0.665	0.261	229	

1 lb = .4536 kg

1 lb/ac = .184 kg/ha

and ended three days later. As shown below, the volume of runoff observed at site P-30 was greater than P-10 but peak discharge was essentially the same.

Site	Streamflow acre ft.	Volume ha-m	Runoff in.	(cm)	Peak Flow cfs	(m^3/s)	Runoff Coeff.
P-10	1614	(199)	1.2	(3.05)	1170	(33.1)	50%
P-30	2829	(349)	1.57	(4)	1100	(31.1)	57%

The greater runoff volume for P-30, almost twice that of P-10, was a result of three factors: (1) larger drainage area, (2) heavier rainfall in the lower basin, and (3) impervious areas in The Woodlands development.

Figures 21 and 22 compare P-10 and P-30 pollutographs for TSS, total COD, TP and TKN. Hydrographs are also presented in the figures for flow rate and time references. Pollutograph analysis should consider the following:

1. Those areas of The Woodlands developed or under construction encompassed only 10% of the total watershed. The majority of stormwater runoff originated in undeveloped forest lands.

2. Developed or construction areas were located adjacent to P-30, as shown in Figure 23. As a result, runoff originating in these areas was observed early in the storm event.

The pollutographs indicate high TSS loads at P-30 (Figure 21), a result of sediments washed from easily eroded construction sites. Although the developing area comprised 10% of the watershed, it contributed as much as 80% of the TSS load at P-30. Total COD (Figure 21) exhibited a "first flush" at P-30, probably due to associated high TSS. The major portion (70%) of the total COD was soluble. Significant increases in TKN and TP at P-30 resulted from wash-off of ammoniated phosphate and urea based fertilizers applied to the golf course in the developing area (Figure 22).

Development within the Panther Branch watershed has resulted in stormwater runoff quality changes. TSS and nutrients have increased although no significant change has been observed for oxygen demand. Results for storm event #10 are summarized in Table 19.

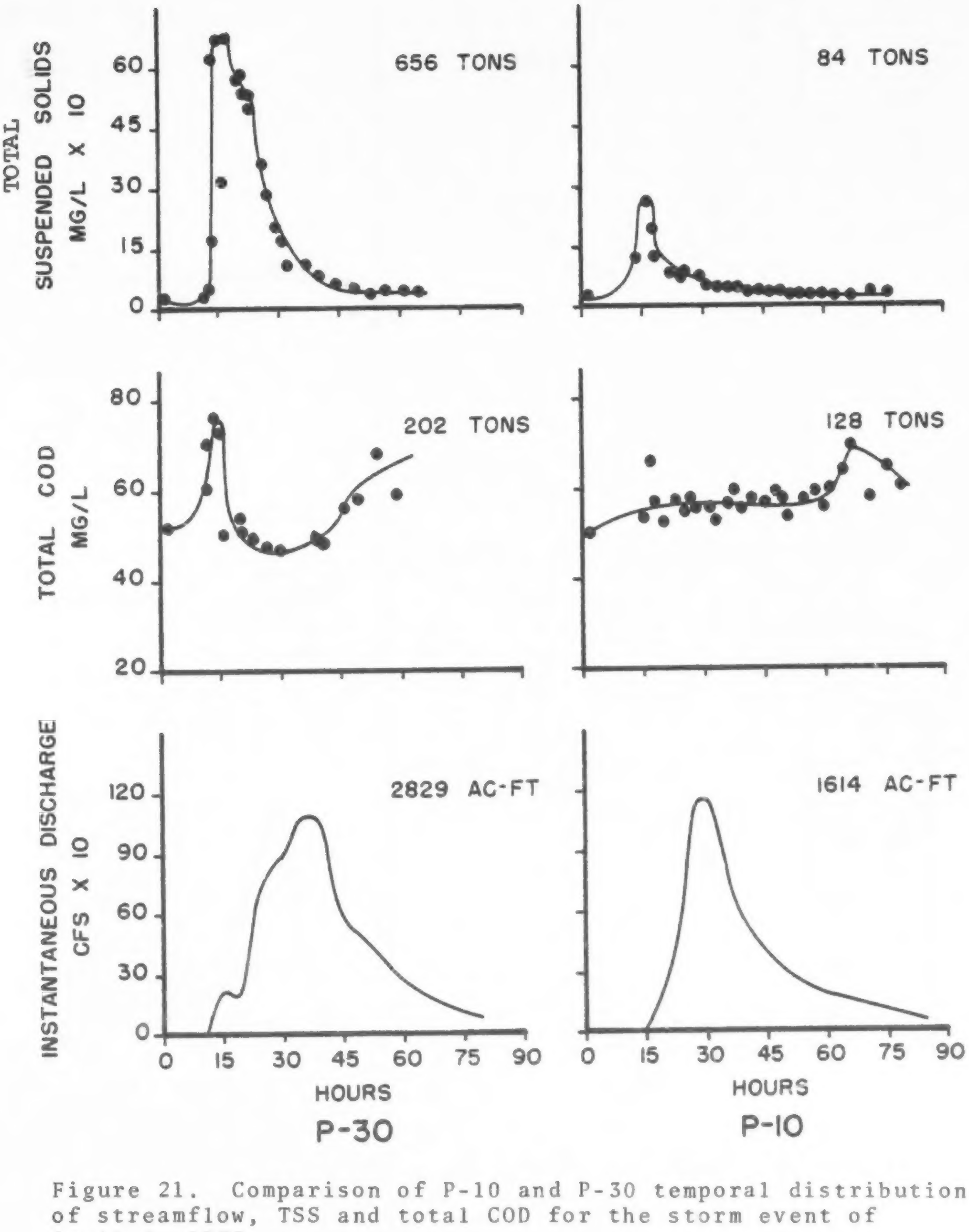


Figure 21. Comparison of P-10 and P-30 temporal distribution of streamflow, TSS and total COD for the storm event of April 8, 1975.

1 cfs = .028 m^3/sec
1 ac ft = .123 ha-m
1 ton = .9078 metric tons

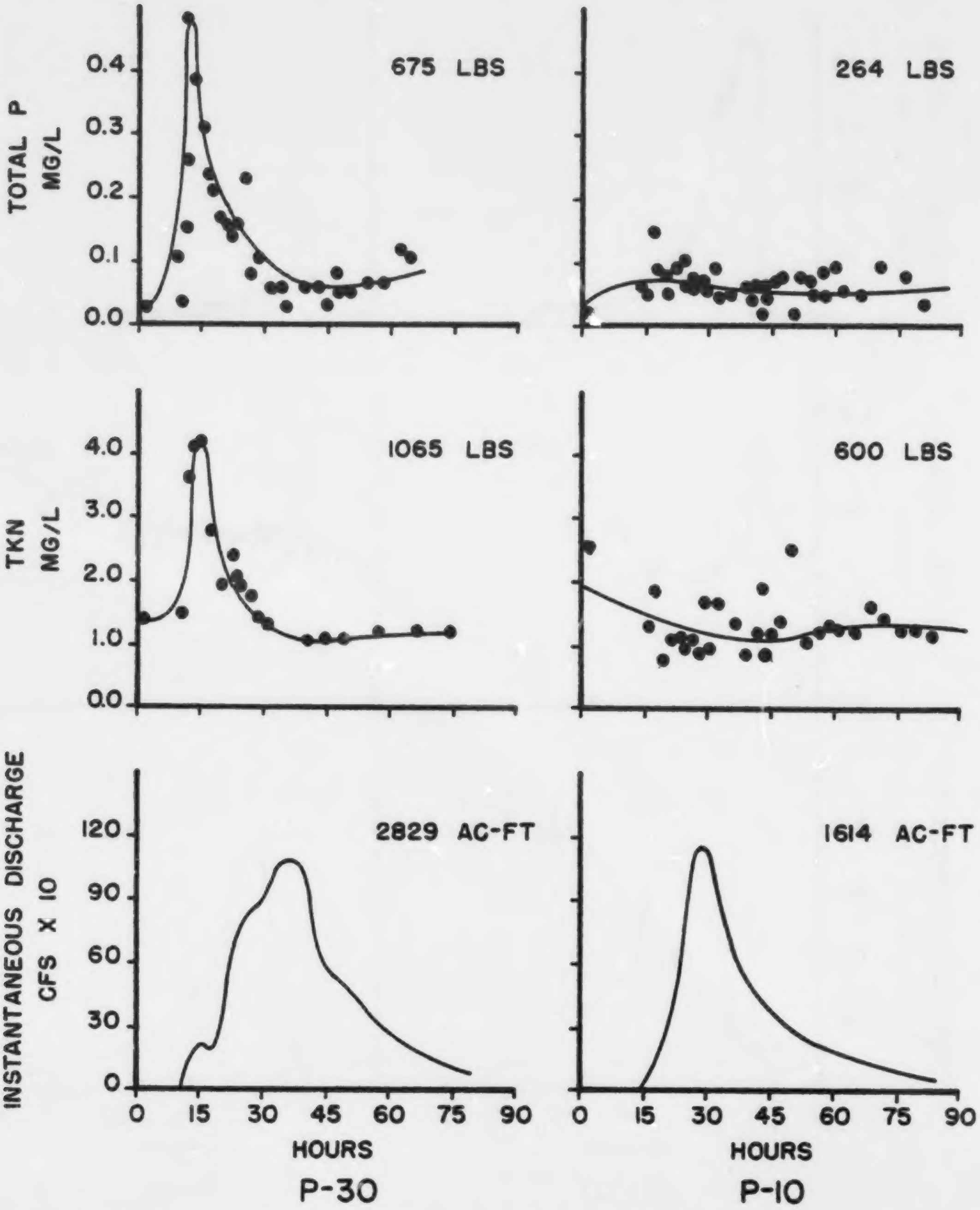
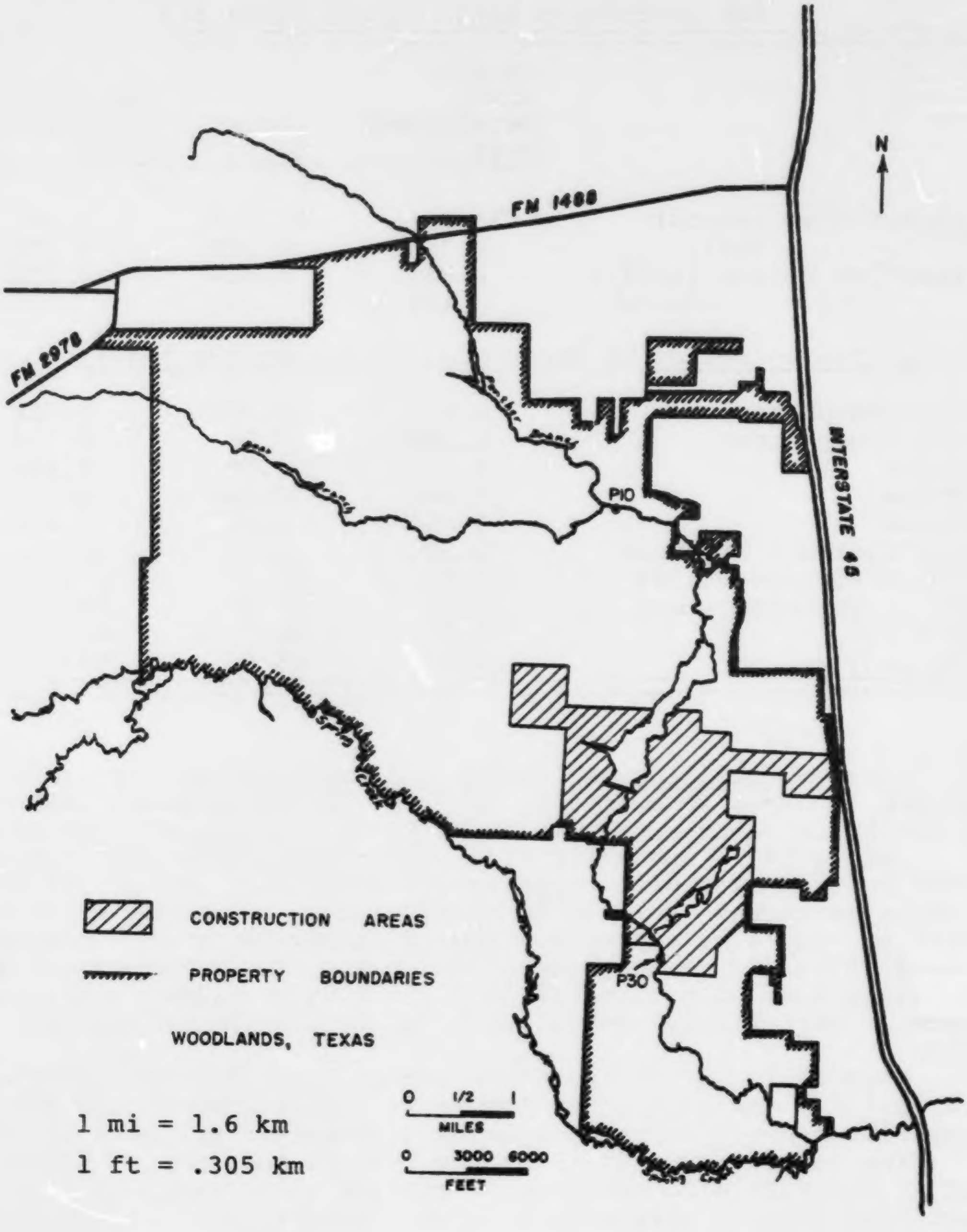


Figure 22. Comparison of P-10 and P-30 temporal distribution of streamflow, TKN and TP for the storm event of April 8, 1975.

1 lb. = .4536 kg
1 ac-ft = .123 ha-m
1 cfs = .028 m^3/sec


N
FM 1488
FM 2978
INTERSTATE 45
P10
P30
Spring Creek
CONSTRUCTION AREAS
PROPERTY BOUNDARIES
WOODLANDS, TEXAS
0 1/2 1
MILES
0 3000 6000
FEET

1 mi = 1.6 km
1 ft = .305 km

Figure 23. The Woodlands construction activity in relation to the P-10 and P-30 sampling sites.

TABLE 19. COMPARISON OF STORMWATER QUALITY AT P-10, P-30 AND DEVELOPING AREAS DURING STORM #10

	Forest with Development P-30	Forest P-10	The Woodlands Development (P-30) - (P-10)
Drainage Area (acres)	21,606	16,050	5,556
(ha)	8,750	6,500	2,250
Streamflow Volume (ac-ft)	2,829	1,614	1,215
(ha-m)	349	199	150
Average Concentration of Water Quality Parameters (mg/l)			
Ortho-phosphate	0.011	0.003	0.021
Total Phosphorous	0.088	0.06	0.125
Ammonia	0.15	0.08	0.244
Nitrite	0.009	0.004	0.017
Nitrate	0.154	0.065	0.272
Total Kjeldahl Nitrogen	1.39	1.37	1.41
Total Suspended Solids	171	38.5	347
Soluble Organic Carbon	20.4	22.0	18.2
Total COD	52.6	58.7	44.5
Soluble COD	38.8	43.0	33.2

FC/FS bacteriological ratios and land use--An important comparison employed in examining data is the relationship between FC and FS concentrations. A FC/FS ratio ≥ 4 suggests the present of human wastes. Between 2 and 4, the FC/FS ratio may suggest human wastes mixed with other source materials, and 1 < FC/FS < 2 value represents an area of uncertainty. If values fall between 0.7 and 1.0, a predominance of livestock or warm-blooded animal waste may be suggested. Following the latter range, FC/FS values less than or equal to 0.7 strongly suggest a predominance of warm-blooded animal waste other than human wastes.

Mean FC/FS ratios for storm events, low flow and sewage determinations are plotted in Figure 24. Note that FC and FS bacterial numbers in The Woodlands stormwaters are greater than low-flow waters, however the ratio remains the same. Urban runoff at Westbury also exhibited a similar ratio although the bacterial numbers were much greater. High ratios for the sewage determinations confirm human waste contamination. Lake B runoff contained the lowest ratios indicating stormwater impoundment may have beneficial effects or that organisms attached to suspended sediment. TC, FC, FS and ST bacterial species were all observed to settle in quiescent water. Additional data have been reported by Olivieri, et al., (44).

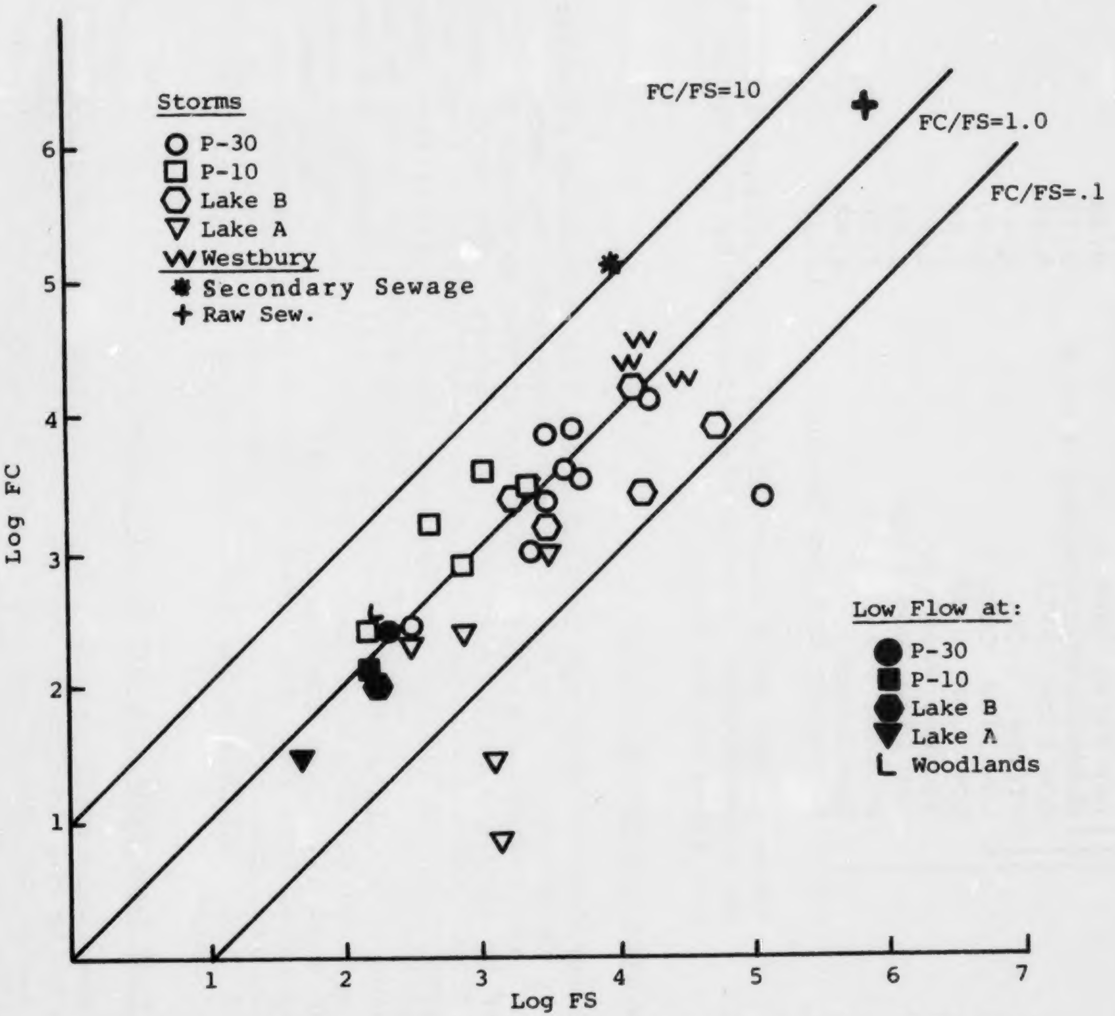


Figure 24. Scalar approach to FC/FS patterns in different land use areas.

A least significant difference statistical analysis was applied to FC/FS ratios from all stations resulting in the following sequence:

Location	FC/FS (Geo. Mean)
Storms, Lake A	0.17
Storms, Lake B	0.53
Low Flow, Lake A	0.58
Chlorinated Secondary Sewage	0.73
Low Flow, P-10	0.92
Storms, P-30	0.97
Low Flow, Lake B	0.99
Low Flow, P-30	1.26
Storms, Westbury	1.47
Low Flow, Woodlands	1.68
Storms, P-10	2.11
Raw Sewage	2.42
Secondary Treated Sewage	13.30

Those groups which demonstrated no significant differences between subsets are indicated by the vertical lines on the side.

STORMWATER QUALITY MODELING

Several techniques are available for the prediction of water quality responses in a watershed. The SWMM model has been adapted for natural drainage conditions at The Woodlands in an effort to simulate stormwater quality response. The model operates from a relation between runoff rate and pollutant load, but the prediction of hydrographs has been more successful than pollutant response. The water quality procedure in the model is not designed to simulate the response from natural drainage, and has been updated for The Woodlands. New relationships between cumulative load (lb) and cumulative runoff volume (ft^3) have been incorporated into SWMM for various parameters at The Woodlands. In this way, concentrations can be predicted as a function of runoff (45). Another water quality modeling approach is discussed below.

Pollutant Load Modeling for Multiple Events

The load-runoff relationships presented above (Figures 17-20) provide the foundation for an uncomplicated, yet satisfactory, model for runoff pollutant load simulation of multiple or individual storm events. Given time increment values for runoff, the model consults time-varying load-runoff relationships to calculate mass flows during storm events.

Variation in the average pollutant concentration over time is approximated by variation of the load-runoff line slopes (Figures 17-20). These slopes represent the ratio of mass of pollutant/time and volume of runoff/time, or mass of pollutant/ volume of runoff which is an average pollutant quality concentration for each watershed. Initially three parameters are defined for each load-runoff relationship: the average slope, the initial slope, and a factor which sets the range within which the slope can vary. The average clope can be roughly determined from the cumulative relationship produced from field data. The initial slope value depends primarily on initial conditions, and the range variable is determined by the spread in observed pollutant concentrations.

During dry periods the slopes are incrementally increased up to but not above the pre-defined maximum. This corresponds to the buildup of available pollutants on a watershed between storm events. An increment chosen to increase the slopes is required as input and is obtained primarily by calibration. During a storm event the value of the slope decays exponentially by the same means employed in both the SWMM (46) and the Storage, Treament, and Overflow Model (STORM, (47).

$$\text{Lbs pollutant washed off in any time interval} \quad \alpha \quad \text{Lbs remaining on the ground}$$

or:

$$\frac{-dP}{dt} = kP \qquad (1)$$

which when integrated takes the form:

$$P_o - P = P_o \ (1-e^{-kt}) \qquad (2)$$

Where $P_o - P$ = lbs washed away in time, t, and k is assumed to vary in direct proportion to the rate of runoff, r:

$$k = br \qquad (3)$$

b can be evaluated given the assumption that 0.5 in. (1.27 cm) of runoff uniformly delivered in 1 hour washes away 90% of the pollutants (22). As a result the equation can be written:

$$P_o - P = P_o \ (1-e^{-4.6\ rt}) \qquad (4)$$

The equation used to decay the load-runoff line slopes is:

$$PDS = 1-e^{-4.6\ rt}\ (PDS)_o \qquad (5)$$

Where PDS is the load-runoff curve slope at some point in time during the storm event and $(PDS)_o$ is the initial value.

A six month period of streamflow at site P-30 was chosen for sequential simulation. This period dating from October 28, 1974 to April 8, 1975 includes storm events 5, 7 and 10 monitored during the study. Storm events 8 and 9 were considered too small for use in the simulation. Predicted solids loads and the observed streamflow hydrographs are presented in Figure 25. Slope parameters used were derived from the load-runoff relationship, with the upper limit values found by trial and error.

Simulation results can be evaluated by comparing observed and simulated mass flows for individual storm events. As shown in Figure 26, the simulated curves compare satisfactorily to the observed mass flow curves. Table 20 gives comparisons of simulated to observed values for total pounds TSS, and peak magnitudes for each of the three storms.

Unit Loadograph for Single Event Simulation

The form of the stormwater mass flow curves, obtained from the product of instantaneous concentration and discharge, resemble the general shape of the streamflow hydrograph and provide a more useful measure of runoff loadings than the concentration curves. For a given watershed, it is possible to generate a unit hydrograph based on the incomplete gamma distribution. Using the theory of linear reservoirs, the resulting equation for the unit hydrograph becomes (48)

$$Q_n = \frac{S}{k\Gamma(n)} \left(\frac{t}{k}\right)^{n-1} \exp(-t/k) \qquad (6)$$

where S = total storage (one inch (2.54 cm) of runoff); k = constant; n = outflow from n^{th} reservoir. The watershed is considered as n serially arranged linear reservoirs, and it is possible to fit an observed hydrograph by varying k and n.

The theory of linear reservoirs can be extended for mass flow curves in order to develop a corresponding unit pollutograph or unit loadograph for application to urban storm runoff. In this way, mass flow curves can be generated in a similar fashion to the hydrograph by varying appropriate constants. The watershed is considered as n serially arranged tanks with first order decay, and the mass balance becomes

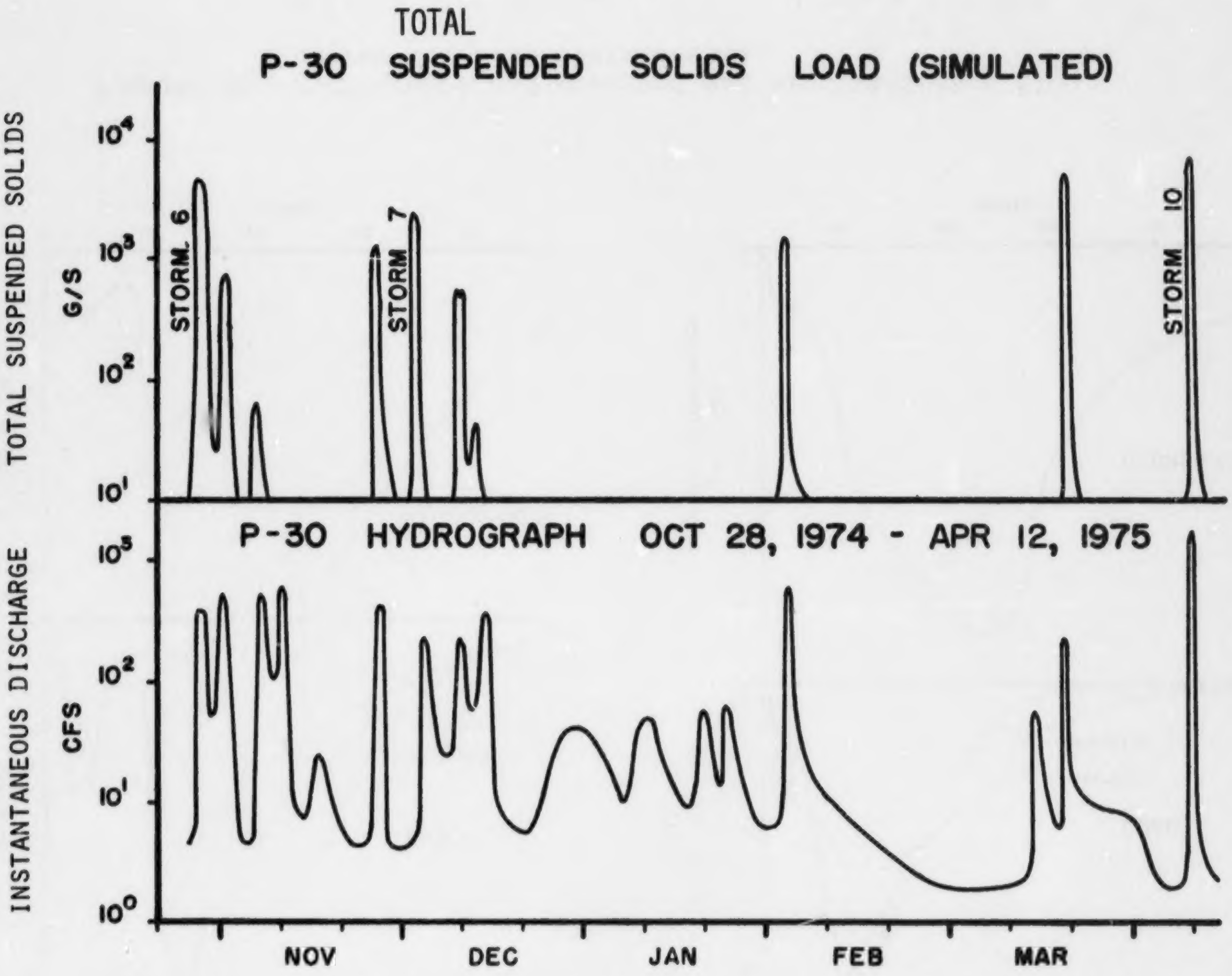


Figure 25. Hydrograph and predicted TSS load for the P-30 Hydrograph period of 10/28/74 to 4/12/75.

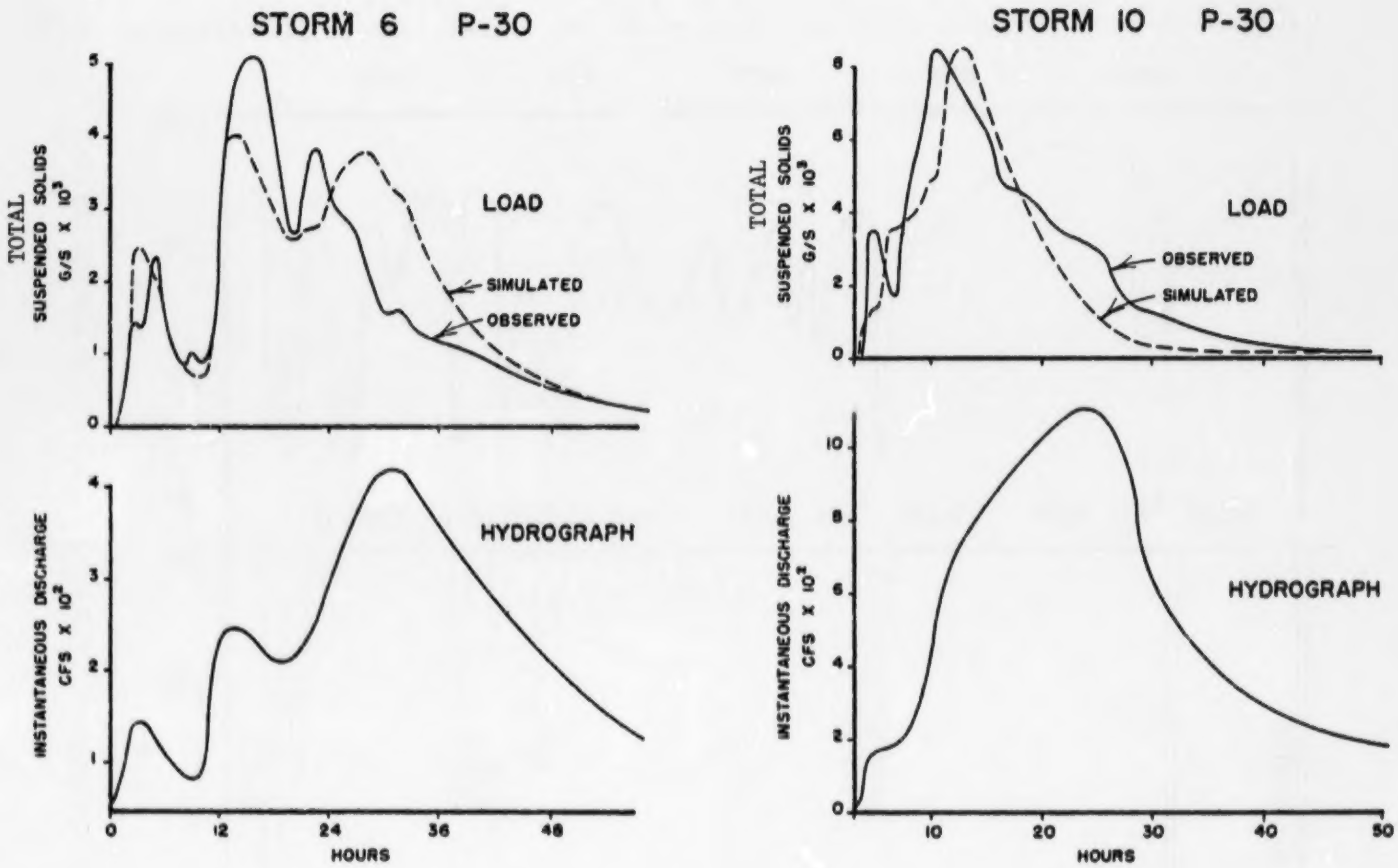


Figure 26. Hydrographs and observed and simulated mass flow curves for P-30 storm events.

1 cfs = .028 m3 /sec 1 g/s = 7.9 lb/h

TABLE 20. A COMPARISON OF SIMULATED AND OBSERVED RESULTS FOR THREE STORMS. STORM #6 IS TRIPLE PEAKED

Storm Number	TSS Pounds x 10^3		% Error	Peaks g/sec				% Error
	Simulated	Observed		simulated	hr.[1]	observed	hr.[1]	
6	880	775	13.5	2600 4100 3900	3 13 27	2500 5200 3900	5 15 22	4 21 0
7	340	296	15	2350	926	2200	926	7
10	853	1312	35	8750	3907	8750	3906	0

note: 1 lb = .4536 kg

[1] Hr. is measured in time since beginning of simulation (10/28/74).

$$\frac{dM_1}{dt} = g_o - g_1 - k_1 M \qquad (7)$$

where M_1 = total mass; g_o = mass inflow; g_1 = mass outflow; k_1 = linear decay coefficient. By solving the equation for n reservoirs in series, assuming outflow from one is inflow to the next, and assuming M = kg (analogous to S = kQ), the final resulting equation for the unit loadograph, defined as the mass flow in kg/sec plotted vs time, becomes

$$g_n = \frac{M}{k\Gamma(n)} \left(\frac{t}{k}\right)^{n-1} \exp(-a/t) \qquad (8)$$

The similarities of equation 8 and equation 6 are obvious, where g_n is mass flow (kg/sec), a equals $(1 + kk_1)/k$, and M is total mass.

Hydrograph and mass flow simulations for Storm 10 on the P-10 site are shown in Figure 27. The timing of the hydrograph peak and the total volume compare well, but the recession rate is predicted lower than the observed. The simulation of TSS and TP mass flow curves (g/sec) yielded similar results, with good peak and total mass definition, but a predicted recession rate lower than observed. This storm yielded 1.2 in (3.05 cm) of runoff, and the unit response can be ovtained by dividing all ordinates by 1.2.

The application of this approach is in a preliminary stage due to lack of significant storm runoff data (1 inch, 2.54 cm, or greater) on Hunting Bayou of The Woodlands watersheds. As more storm event data are collected from other watersheds in the area, it will be possible to investigate relationships between the gamma distribution shape parameters (n, k) and land use or physiographic factors in the watershed. In general, the time of peak of the unit loadograph is related to n and k by the equation

$$t_p = \frac{(n-1)k}{1+kk_1} \qquad (9)$$

Urbanizing watersheds should have lower values of n and k than undeveloped watersheds of the same size. As n is increased, k must be correspondingly decreased in order to yield the same t_p value for a given watershed.

The unit loadograph can be used in the same manner as the unit hydrograph. Once the unit response has been determined for a watershed, storms of varying intensity can be analyzed by lagging and superposition of the unit graphs. A unit pollutograph (concentration vs time) is found by dividing the ordinates of the

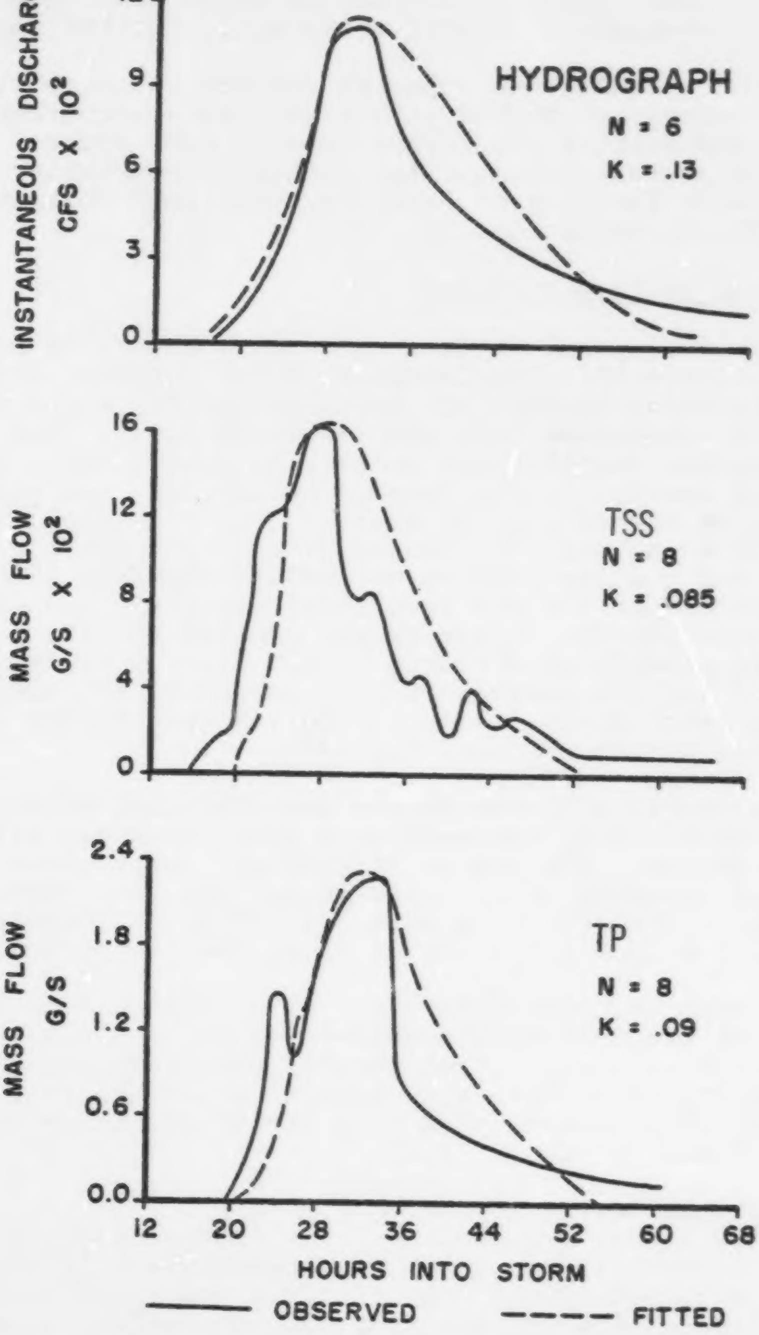


Figure 27. Fitted curves for storm runoff and pollutant mass flows observed at P-10 on 4/8/75.
1 cfs = .028 m^3/sec

unit loadograph by corresponding hydrograph flows. Because of the linear load-runoff relationships which have been developed, the linear assumption of unit response is further justified.

The unit loadograph approach suffers the same limitations as the unit hydrograph method with regard to assumptions of uniform rainfall and initial conditions, but it does offer a relatively simple and useful technique for analyzing stormwater pollution response as a function of land use, watershed characteristics, and hydrologic conditions.

Storm Water Management Model

SWMM is composed of five integral computation blocks as shown in Figure 28. The Executive Block controls all activity within the model because all input-output functions for other blocks are programmed into the Executive Block. The Runoff Block computes quantity and quality of runoff for a given storm and stores results in the form of hydrographs and pollutographs at inlets to the main sewer system. The Transport Block sets up initial flow and infiltration conditions and performs flow quantity and quality routing to produce combined flow hydrographs and pollutographs for the total drainage basin and at selected intermediate points. Quantity and quality of flow are stored and treated by predefined criteria in the Storage Block. Dispersion effects of the discharge in receiving waters are computed in the Receiving Water Block. A more detailed description is available in the User Manual - Volume III (46).

In general, only one or two computational blocks, as well as the Executive Block, are used in a run. However, all blocks may be run together. The use of independent computation blocks allows for examination of intermediate results. The necessity for at least 350K bytes of core storage in SWMM leads to high run costs and limits the number of options to be analyzed.

The SWMM release of February 1975, referred to in this report as the original SWMM version, was extensively modified. The capabilities of the modified version have been expanded to model runoff and water quality from natural drainage areas. Study areas where new capabilities were tested are The Woodlands and Houston, Texas (45).

Model Application--

Specific data required as input to the original SWMM are described in Table 21. A quantified description of the watershed provides a computational basis for the model and includes the rainfall hyetograph for the storm to be modeled, a physical description of each subcatchment to be modeled including the drainage area, percent of impervious cover, ground slope, Manning's roughness factors, estimated retention storage for both the pervious and impervious surfaces, and the coefficients to define

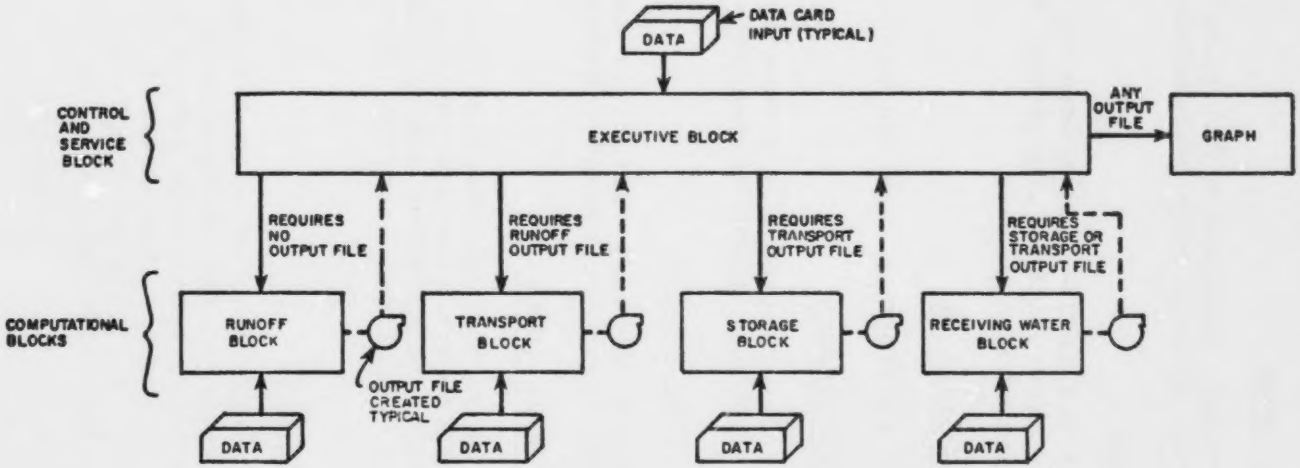

DATA
DATA CARD INPUT (TYPICAL)
CONTROL AND SERVICE BLOCK
EXECUTIVE BLOCK
ANY OUTPUT FILE
GRAPH
REQUIRES NO OUTPUT FILE
REQUIRES RUNOFF OUTPUT FILE
REQUIRES TRANSPORT OUTPUT FILE
REQUIRES STORAGE OR TRANSPORT OUTPUT FILE
COMPUTATIONAL BLOCKS
RUNOFF BLOCK
TRANSPORT BLOCK
STORAGE BLOCK
RECEIVING WATER BLOCK
OUTPUT FILE CREATED TYPICAL
DATA
DATA
DATA
DATA

Figure 28. Master programming routine in the SWMM.

TABLE 21. MODELING REQUIREMENTS BY SWMM (46)

Item 1. Define the Study Area

Land use, topography, population distribution, census tract data, aerial photos, area boundaries.

Item 2. Define the System

Furnish plans of the collection system to define branching, sizes, and slopes. Types and general locations of inlet structures.

Item 3. Define System Specialties

Flow diversions, regulators, storage basins.

Item 4. Define System Maintenance

Street sweeping (description and frequency). Catchbasin cleaning. Trouble spots (flooding).

Item 5. Define the Receiving Waters

General description (estuary, river, or lake). Measured data (flow, tides, topography, water quality).

Item 6. Define the Base Flow (DWF)

Measured directly or through sewerage facility operating data. Hourly variation and weekday vs. weekend. DWF characteristics (composited BOD and TSS results). Industrial flows (locations, average quantities, quality).

Item 7. Define the Storm Flow

Daily rainfall totals over an extended period (6 months or longer) encompassing the study events. Continuous rainfall hyetographs, continuous runoff hydrographs, and combined flow quality measurements (BOD and TSS) for the study events. Discrete or composited samples as available (describe fully when and how taken).

Horton's soil infiltration equation. Input data also define hydraulics for the storm sewer system in each subcatchment and the main sewers or open channels in terms of gutter length, slope, bottom width, and roughness coefficient, cross-sectional area, side slopes, channel slope, and roughness factor. For water quality modeling, a code defining the specific land use in each subcatchment as well as the street-cleaning frequency, the number of dry days prior to the storm event, the number of catch-basins per unit area and the quality of their contents must also be specified.

Horton's infiltration equation is used to calculate the infiltration rate of rainfall into the soil as a function of time by Horton's relationship (49).

Manning's roughness coefficients were necessary for each drainage element to describe the hydraulics of the drainage system. Gutters and open channels were assigned an initial value of 0.10, while a value of 0.03 was used for sewers. These values were adjusted during model calibration to accommodate higher peak flows. Combined sewers are not used in any of the study areas and therefore all initial flows were zero.

A 10 minute time interval was the limit for modeling accuracy at minimum cost, and all SWMM runs were made with regard to this condition.

Hunting Bayou Modeling--

Input data for the Hunting Bayou drainage system were obtained from existing engineering maps and site inspection. The subcatchments and drainage network used as input data are shown in Figure 29. The total drainage area of 1976.8 acres (499.86 ha) is divided into 24 subcatchments ranging in area from 25 acres (10.11 ha) to 138 acres (55.85 ha). Each subcatchment was assigned a land use class for modeling water quality in SWMM. The drainage system includes 23 gutters and pipes in the Runoff Block and 44 manholes and conduits in the Transport Block. Infiltration rates were originally estimated and then calibrated by consecutive modeling runs.

Five storms were modeled initially. The rainfall data for these storms were obtained from reports published by the U.S. Geological Survey. All five storms occurred during 1968 and 1970, prior to the initiation of this project. Consequently, only water quantity was modeled and no water quality data were available. Comparisons of observed and computed hydrographs for these five events, presented in Table 22, indicate reasonable agreement. The average absolute error in runoff volume was 26% (see Table 22) of the observed value, while the average error in peak flow prediction was 20% of the observed. The temporal agreement of the hydrographs was very good. For instance, the times of peak flow agreed within ten minutes in four of the five instances and

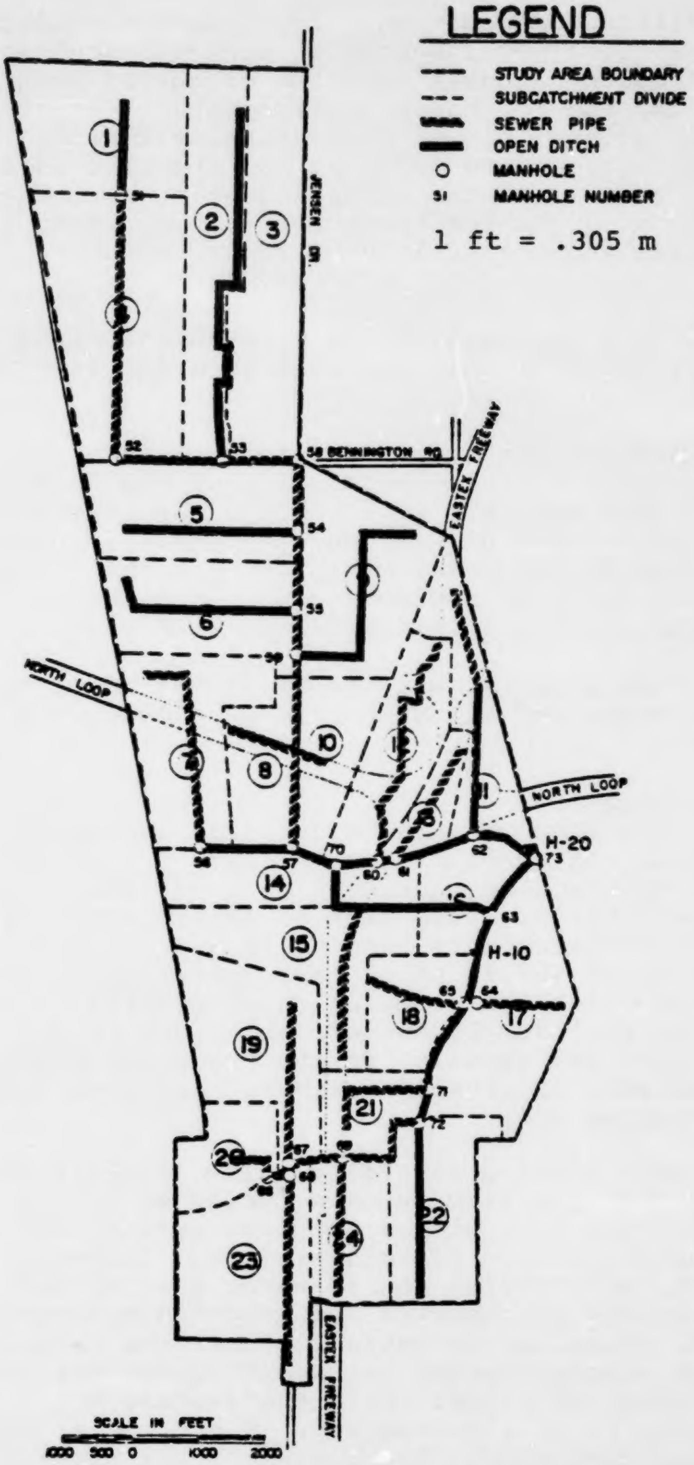

LEGEND
STUDY AREA BOUNDARY
SUBCATCHMENT DIVIDE
SEWER PIPE
OPEN DITCH
○ MANHOLE
51 MANHOLE NUMBER
1 ft = .305 m
JENSEN DR
BENNINGTON RD
EASTEX FREEWAY
NORTH LOOP
NORTH LOOP
H-20
H-10
EASTEX FREEWAY
SCALE IN FEET
1000 500 0 1000 2000
1
2
3
4
5
6
7
8
10
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Figure 29. Subcatchments and drainage network in Hunting Bayou.

average error was twenty-two minutes. However, computed values tended to predict faster returns to low-flow conditions than were actually observed.

TABLE 22. COMPARISON OF SWMM PREDICTED RESULTS WITH OBSERVED FLOW MEASUREMENTS FOR HUNTING BAYOU STORM EVENTS

Date of Storm	Total Runoff ($ft^3 \times 10^6$)		Peak Flow Rate (cfs)	
	Measured	Predicted	Measured	Predicted
09/08/68	4.84	4.50	325	303
09/17/68	9.06	4.98	330	302
11/05/68	4.40	5.07	282	337
10/22/70	12.69	12.84	665	549
11/09/70	1.52	2.46	160	205

NOTE: 1 cfs = .028 m^3/sec

Three more recent Hunting Bayou storms on 3/26/74, 4/11/74 and 5/8/75 were sampled and the water quality and flow prediction capability of the SWMM was tested. The 5/8/75 storm event will be presented here as an example. Figure 30 shows the observed and SWMM predicted hydrographs for this event.

Original SWMM predictive capabilities are based upon dust and dirt accumulation data acquired in Chicago, and the extrapolation of these data to natural drainage areas is a limitation of the model, which resulted in poor water quality predictions for this watershed. Consequently, a simplified approach to water quality prediction in SWMM was developed which does not consider pollutant buildup or input data on dry days, street cleaning frequency, land use, or curb length. Instead, pollutant availability loading rate at the beginning of the storm is input. This information was produced by The Woodlands project stormwater monitoring program. The user determines effects of dry days, street cleaning frequency and land use external to the model.

The new SWMM version was also run for the 5/8/75 storm event, and the resulting predicted TSS pollutograph is shown in Figure 31 (left-hand figure). The loading rates used for this pollutograph prediction are as follows:

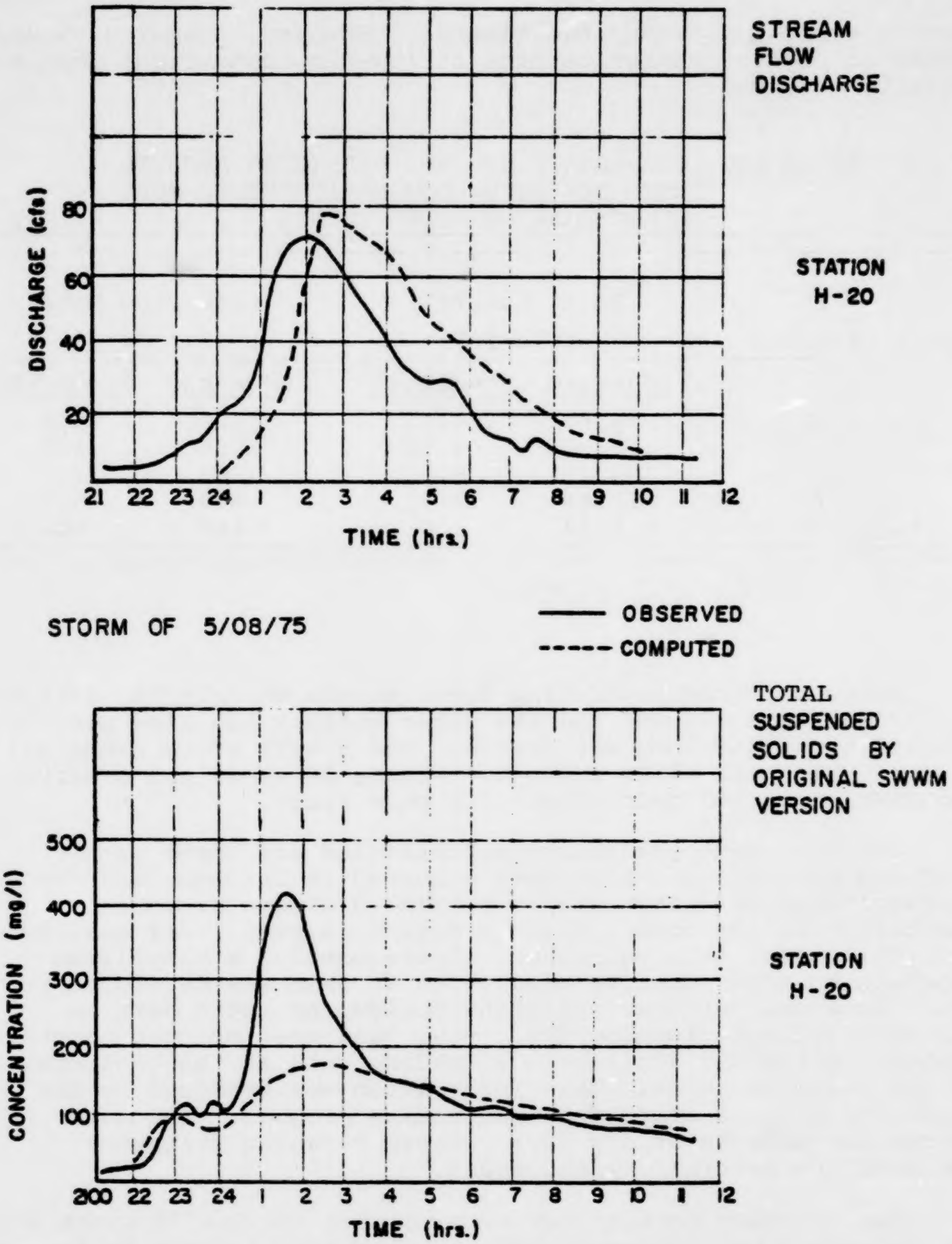
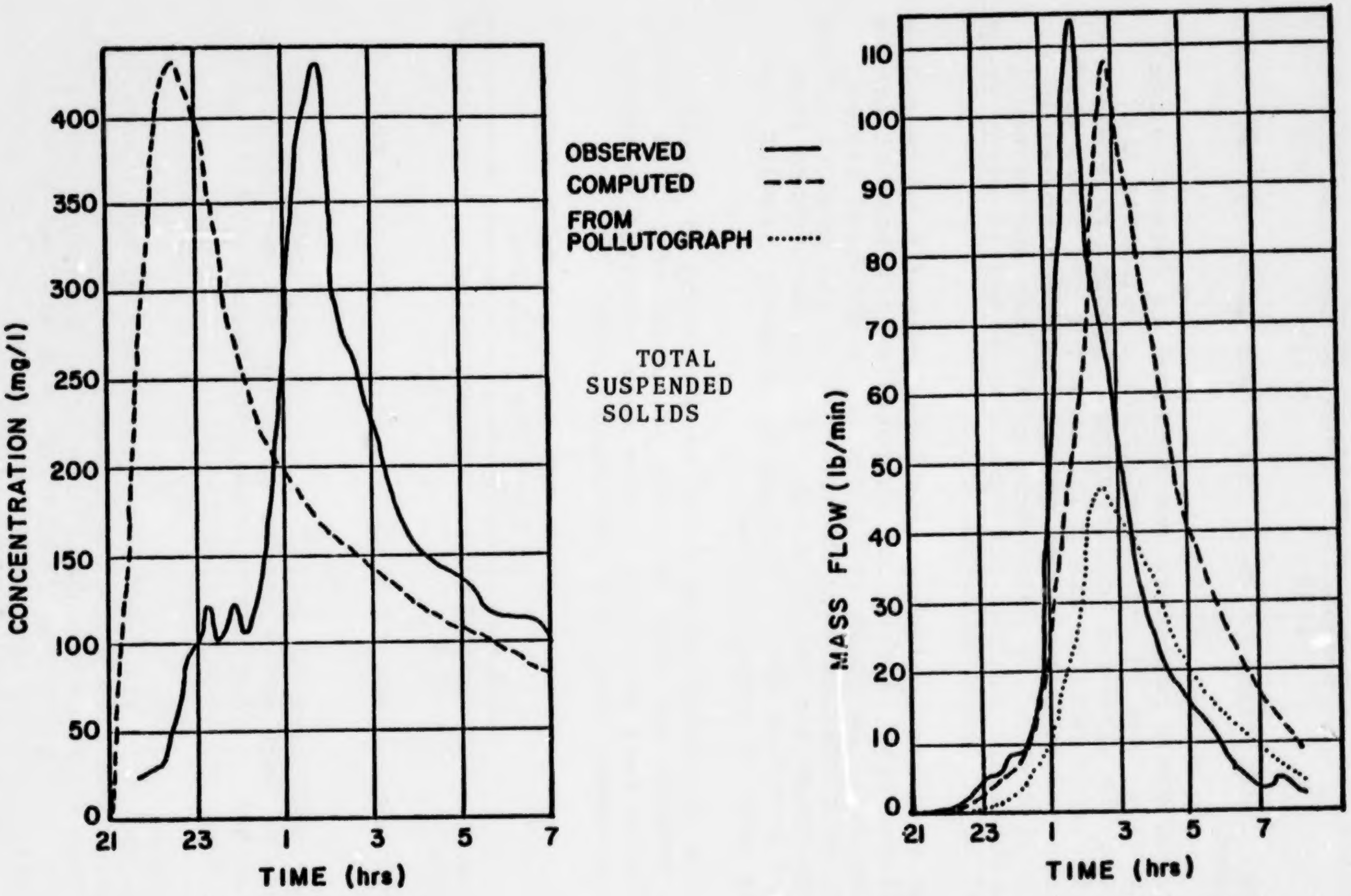


Figure 30. Predicted hydrographs for TSS concentrations at Hunting Bayou (5/8/75).

1 cfs = .028 m^3/sec



(POLLUTOGRAPH) (MASS FLOW CURVES)

Figure 31. Predicted and observed pollutographs and mass flows for TSS at Hunting Bayou (5/8/75). Mass flow rates represent the computed concentration shown on left-hand side of figure. 1 lb/min = 7.56 g/sec

Pollutograph Prediction	TSS Loading Rate According to Land Use (lb/acre)		
	Residential	Construction	Undeveloped
	1.85	2.31	0.23

A removal coefficient of 21.2 min^{-1} was used, as compared to 4.6 in the SWMM.

A trial and error procedure was followed to determine the above loading rates and removal coefficient combination that would reproduce the observed pollutograph. Loading rate and removal coefficients derived are valid only for the storm used for calibration and application of results to other storms is possible only if prevailing antecedent conditions and rainfall-runoff intensities are similar for both storms and if study areas are identical or at least homogeneous.

Although simulated pollutographs were curve-fit to reproduce observed pollutographs, actual and computed mass transport graphs did not correspond. As shown in Figure 31 (right-hand figure, dotted line), poor results were obtained using the product of the predicted hydrograph and pollutograph. It was determined that this condition resulted from a failure to properly predict the timing of the peak of concentration.

To improve the modeling of total mass loading of a pollutant the new version was used to model pollutant mass flow rates. Again the loading rate and decay factor were adjusted to reproduce mass flow rates, using the following values:

	TSS Loading Rate According to Land Use (lb/acre)		
Mass Flow Prediction	Residential	Construction	Undeveloped
	4.0	5.0	0.5

A removal coefficient of 35 min^{-1} was used for this case.

Results, shown in Figure 31 (right-hand figure), indicate mass flow rates can be accurately predicted using this method (dashed line). The method was applied to other stormwater quality parameters, COD, NO_3, TP, with similar results.

Panther Branch Modeling--

The data input to the SWMM for the Panther Branch drainage system was developed from existing engineering maps and numerous site inspections of the watershed. The total drainage area for Panther Branch of 21607 acres (874.40 ha) was divided into 57 subcatchments ranging from 21 acres (815 ha) to 1366 acres (552.80 ha). The input parameter called "width of subcatchment" is defined as the width over which overland flow occurs. Values for this parameter were first estimated by the method described in the SWMM User's Manual (46). These values were subsequently reduced by approximately 40% to achieve calibration. The Panther Branch drainage system is made up of 57 "gutters" and 61 transport elements of varying characteristics.

A major drawback of SWMM at The Woodlands is that the area below P-10 was in a transient state due to development. Continually changing land use affects the quality of runoff and consequently P-10 is regarded as a control point. The area above this gage is in a relatively stable condition and will give a more accurate measurement of the pollutant loading due to the land use rather than from a construction area. Stormwater runoff from a construction area can vary in quality from storm to storm depending on the stage of construction, and modeling proved difficult. Consequently, it is presumed that several construction areas where the natural ground had been disturbed and stripped of the protective vegetative cover contributed more TSS than SWMM could predict from available input data.

Five storm events on Panther Branch have been modeled. Similar to the data for Hunting Bayou, all subcatchment, gutter and transport element data for Panther Branch were identical for all runs. Infiltration rates were determined similar to Hunting Bayou. The original SWMM was used to model both water quantity and quality for two storm events on 10/28/74 and 12/5/74 and only quantity of flow for the remaining events (1/18/74, 4/8/75 and 11/24/75). Computed flow peaks and volumes agreed well with the observed flows; the average absolute error in the volume of runoff between observed and computed hydrographs was good except for the storm events of 10/20/74 and 11/25/74 when the flow peaks between observed and computed hydrographs were approximately three hours apart. Water quality modeling at P-30 was not acceptable using the original SWMM. The 10/28/74 storm event at P-30 was a multi-peaked hydrograph, and TSS modeling by the original SWMM was not accurate. The maximum observed TSS concentration of 1000 mg/l during the second peak in streamflow was computed to be 273 mg/l, a much lower concentration. Runoff quality modeling of the 12/5/74 storm event was similarly too low in concentration and total load.

The 12/5/74 storm event was modeled for both the upstream gage, P-10, and the downstream gage, P-30. Since the entire drainage area had the same land use before development began, most differences between the upstream gage and the downstream gage can be attributed to the changing land use in the developing area. Using the original SWMM version, the computed peak concentration of 142 mg/l TSS at Station P-10 was in good temporal agreement with the observed value of 130 mg/l. The falling limb of the observed pollutograph occurred more rapidly than the simulation pollutograph, resulting in a difference of 11,330 kg (25,000 lb) or a 40% error in computed total load. Observed TSS production at Station P-10 was about one-third that at Station P-30.

The modified water quality version of SWMM was also used to model the 12/5/74 storm on Panther Branch for TSS, COD, NO_3 and TP parameters. The pollutographs and mass flow curves were separately computed using loading rates obtained by trial and error. Simulation results are summarized in Table 23. Optimized pollutograph and mass flow curves corresponded well with the observed data. However, mass flow rates calculated from the optimized pollutographs were not as accurate as computed optimized mass flow rates. TSS predictions at Station P-30 were compatible to observed data with slight differences for occurrence of peak flow rates. Modeling of TP at both P-10 and P-30 and NO_3 at P-30 not entirely satisfactory.

Swale 8 Modeling, Existing and Future Development--

Existing drainage and planning maps were used to develop the input data for Swale 8, the watershed above Lake Harrison. Site inspections to determine drainage area boundaries and extent of construction were conducted on a periodic basis because this watershed was in a transitional stage. During the project, the channel was enlarged and construction of Lake C was underway whiles Lakes A and B had already been filled.

The total drainage area for Swale 8 of 459.3 acres (185.87 hectares) was divided into 10 subcatchments ranging from 23 acres (9.30 ha) to 66 acres (26.71 ha). Land uses for the upstream subcatchments were classified as open space, whereas the last three downstream subcatchments were designated as multi-family, residential and commercial. Seventeen drainage system elements were used to model the entire area. Of these, two elements were storage units, Lakes A and B, and all six channels were trapezoidal in shape as a result of channel enlargement.

Swale 8 storm even on 4/8/75 was modeled because the only other observed storm event, 3/13/75, had a peak inflow into Lake B of 0.06 m^3/sec (2.0 cfs) from 0.81 in. (2.06 cm) of rainfall.

The transitional phase of development in Swale 8 gave rise to several problems in modeling runoff. The most severe problem is the lack of lake volume data. The topographic maps prior to lake construction show the natural ground contours, but the reservoir areas were used as borrow pits for fill material for the dams as well as other construction at The Woodlands. Consequently, the original storage capacity of the reservoirs was not known and no subsequent reservoir surveys have been conducted; therefore, the elevation-area-capacity data for these lakes were

TABLE 23. WATER QUALITY MODELING RESULTS FOR PANTHER BRANCH FOR STORM EVENT OF 12/5/74

	Observed Data			Pollutograph Reproduction			Pollutant Mass Transport Rate Reproduction		
	Peak Conc. mg/1	Peak Mass lb/min	Total Mass $lb \times 10^3$	Peak Conc. mg/1	Peak Mass lb/min	Total Mass $lb \times 10^3$	Peak Conc. mg/1	Peak Mass lb/min	Total Mass $lb \times 10^3$
				STATION P-10					
TSS	130.	27.		137.	48.		75.	27.	
COD	60.	66.		60.	35.		113.	66.	
NO_2^-	.092	.045		.092	.037		.105	.043	
$PO_4^=$	.20	.19		.52	.229		.433	.115	
				STATION P-30					
TSS	670.	290.	296	588.	233.	204.	814.	296.	205.
COD	63.	73.	196.	73.	35.	76.	169.	71.	149.
NO_2^-	.276	.13	.08	.284	.068	.09	1.67	.38	.24
$PO_4^=$	.53	.18	.33	3.2	.524	.72	.723	.114	.24

NOTE: 1 lb/min = 7.56 g/sec

only approximate. Also, groundwater was being pumped in Lake A and pumpage rate was not recorded.

The outflow structure for Lake A is controlled by different outlets at different water surface elevations. The outflow rating curve (discharge as a function of water surface elevation) is composed of three segments, one controlled by the low-flow orifice, the second controlled by weir flow through the flood discharge outlet which in turn is limited at extreme flows by the capacity of the outfall conduit and resulting in the third segment of the rating curve. The SWMM is not capable of modeling this complex outflow scheme.

Under the conditions described above, the modeling of runoff storage in the lakes proved to be difficult. Several attempts to model the outflow from Lake A for the storm of 4/8/75 were unsuccessful. The extent of assumed data was too large in magnitude to approximate the correct operation of Lakes A and B. As a result, additional modeling of the watershed was conducted only on that drainage area of Swale 8 upstream from Lake Harrison at point P-10 (Lake B gaging station). The results of this modeling effort are discussed in the following paragraphs.

Due to various external influences, urban development at The Woodlands did not proceed as rapidly as expected. Site development plans were available for Phase I, and in early 1976 a major portion of the Swale 8 watershed was being planned for development. Using these plans for the watershed, three development scenarios were evaluated for modeling: (1) existing conditions, (2) immediately developing conditions, and (3) future but not ultimate conditions.

Water quality predictions by the modified version of SWMM were attempted. Changes in land use and increase in imperviousness were computed from plat maps provided by The Woodlands Development Corporation and input to the SWMM. As described earlier, the modified quality prediction version required the input of loading rates for each pollutant. The initial loading rates used were derived from the P-30 watershed modeling experience. Based on previously described experience with pollutograph differences resulting from computed hydrographs, it was decided that only mass flow rates would be modeled. Runoff from the storm on 4/8/75 was chosen for modeling; however, due to its multi-peak complexity, only the first hydrograph peak was modeled. Results from the first computer run indicated that the loading rates determined from the results of modeling at Station P-30 were too low. Observed peak mass flow of TSS was three times the peak mass flow computed from loading rates derived at Station P-30. These differences are a result of the extreme effects of lake and golf course construction, as well as channel improvement concentrated in the Swale 8 watershed. Also the freshly sodded,

TABLE 24. MODELING RESULTS FOR FUTURE DEVELOPMENT UPSTREAM FOR LAKE B

	Peak Conc. mg/1	Peak Mass lb/min	Total Mass lb
		OBSERVED DATA	
TSS	2152.	608.	303051
COD	87.	31.5	13290
Nitrates	2.105	.113	30
Phosphates	.359	.130	21
		EXISTING CONDITIONS	
TSS	6348.	609.	65290
COD	217.	31.	3539
Nitrates	.93	.108	9
Phosphates	2.32	.129	9
		CONSTRUCTION CONDITIONS	
TSS	5713.	1080.	97163
COD	231.	35.	4232
Nitrates	.98	.099	11
Phosphates	2.34	.133	12
		DEVELOPED CONDITIONS	
TSS	5706.	1289.	95415
COD	231.	68.	5862
Nitrates	.98	.214	16
Phosphates	2.34	.289	21

developed areas severely eroded during the intense rainfall of this period. Loading rates were revised for both construction and developed areas. For Swale 8 the TSS loading rates from developed areas were 82% of the rate from construction areas. In contrast, the same ratio at Station P-30 was 78%.

The modified version of SWMM was run for two future watershed development conditions described earlier, using the rainfall on 4/8/75 to provide a basis for comparison between existing and future conditions. As anticipated, the larger proportion of area under construction changes the pollutant loads considerably; the changes range from an increase of 77% for TSS to a decrease of 8% for nitrates.

After the construction phase of development has been completed, peak pollutant loads do not decrease as may be expected, but the total mass of pollutant do decrease. These dramatic environmental effects of construction activities are listed in Table 24. One reason for the increase in peak mass flow rates is the change in the runoff hydrograph. After construction the hydrograph peak is increased by approximately 40%. Another reason is the increase in the input loading rates for developed areas, which results in a doubling of peak mass flow rates for the parameters NO_3, COD and TP. The 20% increase in the TSS mass flow rate is a result of hydrograph modification due to urbanization.

In summary, the modified water quality modeling version greatly improved the capabilities of the SWMM. Water quality modeling results are much more dependable, and observed events can be adequately simulated. Each of the storms used to test the new SWMM version was selected to present a range of flow, water quality and land use data; thus, the model was tested over a range of different conditions.

STORMWATER ALTERATIONS AT THE WOODLANDS

Water Quality Needs

Irrigation--

Collected stormwaters are to be used for golf course irrigation at The Woodlands to supplement natural precipitation. The critical water quality parameter for irrigation is salinity. Excessive salinity affects plants by increasing osmotic pressure in the soil which limits uptake of water by plants. However, this is not the case at The Woodlands and, therefore, salinity will not be a problem. Electrical conductivity measurements in stormwater runoff is less than 3000 micromhos at The Woodlands and is "excellent to good for most plants" (50). The presence of nutrients in stormwaters slated for irrigation is not high and in this case considered an asset rather than a pollutant. TSS concentration or large particulates could cause mechanical problems such as pump damage or clogging of sprinkler heads, but careful placement of the intake structure will avoid these difficulties. TSS concentration in Lake Harrison during low-flow conditions is about 100 mg/l and average particulate size is estimated between 25 and 250 mg/l, levels acceptable for pumping requirements. The velocity in the distribution system will keep the solids in suspension. Particulate size criteria will be set by the orifice size of the irrigation system.

Aesthetics--

The water quality level for aesthetics is presently met without any stormwater treatment. The lake is devoid of floating debris or objectionable odors and promises to support a wide variety of life-forms. Superficially, it resembles early stages of other local man-made lakes. High nutrient levels may promote macrophyte growth and algal blooms, but macrophytes can be controlled by a regular lake maintenance program and algal blooms can be prevented by reducing the lake detention times and nutrient levels (40).

Recreation--

In a discussion of recreational water uses, two divisions must be considered: contact and noncontact. The water quality requirement for contact recreation, which involves substantial risk of ingestion, is more stringent than that of noncontact (51). Swimming is the primary example of contact recreation and is prohibited in The Woodlands' lakes.

A water quality criteria designed strictly for boating would be similar to that for aesthetics, with the added requirement for fecal coliform levels. It is recommended that fecal coliform levels of 2000/100 ml average and 4000/100 ml maximum be observed for "unofficial recreation" waters. Levels of 1000/100 ml average and 2000/100 ml maximum were suggested for official noncontact waters (52). Fishing water criteria invoke an additional requirement that harvested species be fit for human consumption. Edible fish species should be free of toxic chemicals and pathogenic bacteria or viruses. The data to determine the fulfillment of this requirement is not presently available. The consumption of fish from such waters has been practiced without harmful results. Coliforms in the digestive systems of fish caught at Woodlands are in higher concentrations than from other lakes but presumably do not reach the edible portions of the fish (52).

Water Supply Uses--

Lake Harrison ranks as a poor raw drinking water source because it would require a high level of treatment before use (50). With groundwater, a less expensive and more reliable source is easily obtained. Its use for this function is to be restricted to emergencies.

The Lake System

The man-made lakes at The Woodlands will serve as recreational centers, wildlife preserves and storage for stormwater runoff. The lakes will contribute to the maintenance of a perched water table necessary for plant life. The lake water will also be used for irrigation of adjacent golf courses. Inputs to the lake system are limited to stormwater runoff and treated wastewater from The Woodlands Wastewater Reclamation Plant with ultimate capacity of 6 mgd (.26 m^3/sec). For a year of average rainfall, treated wastewater will comprise 75% of the flow through the lake system. Design effluent quality for the plant is indicated in Table 15 and suggests that the lakes will contain clear waters with somewhat elevated nutrient concentrations as compared to existing surface waters. Lake detention time during dry weather will be approximately six days. Consequently, treated wastewater will be the dominant influence on lake water quality at The Woodlands.

The lakes will serve as stormwater storage reservoirs and, in so doing, will remove significant amounts of pollutants, primarily due to sedimentation.

Lake Harrison Sedimentation--

Eight storm events were monitored at the lake system, ranging from 0.26 in. (0.66 cm) to 3.97 in. (10 cm) of rainfall. In the following paragraphs, the largest storm indicates the usefulness of reservoirs for preventing release of construction site sediment washoff.

Rainfall associated with the storm event began shortly after midnight on April 8, 1975 and continued until noon the same day. An early morning cloudburst was followed after a four hour pause by less intense rainfall totaling 3.97 in. (10 cm). The hyetograph is shown in Figure 32. Runoff passing the Lake B gaging station, the major inflow to Lake Harrison, originated in a watershed undergoing intense development at this time. Much of the drainage system itself was being constructed under specifications of the "natural drainage" system including Lake C, 656.2 ft (200 m) upstream of Lake B. Lake C was constructed to serve as a wet weather pond and golf course water hazard. Unfortunately, its low earthen spillway had yet to be sodded and provided an erosion source within the drainage channel.

Lake Harrison inflow and outflow hydrographs are compared in Figure 33. Characteristic of runoff response in a small watershed, the multi-peaked inflow hydrograph was a product of the sporadic hyetograph (Figure 32). Intense stormwater flow deepened the inflow channel by 6 in. (15 cm) and obliterated bales of

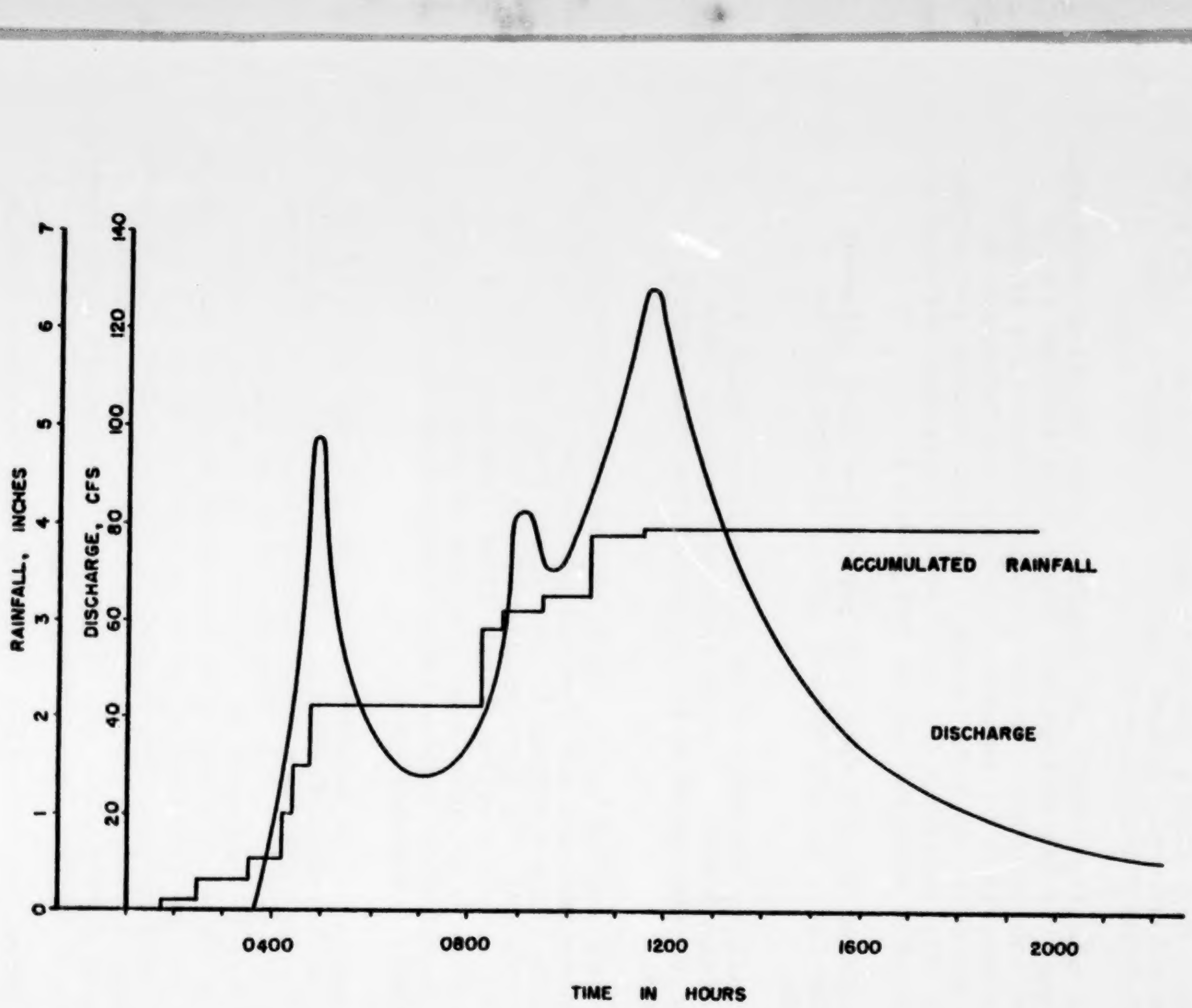


Figure 32. Hydrograph and cumulative hyetograph at the Lake B gauging station for the April 8, 1975 storm event.

1 in. = 2.54 cm

1 cfs = .028 m^3/sec

hay placed in the channel to act as flow control devices. Stormwater flow crested shortly before noon on April 8 at a record discharge of 123 cfs (3.48 m^3/s). Bank storage and ponding helped to prolong minimum flow in the channel for two days, contributing to the total inflow runoff volume of 93 acre ft (114 m^3). The lake system effectively damped inflow fluctuations. The hydrograph peak traveled through the lakes in a half hour.

Stormwater quality--Table 25 compares flow weighted mean and maximum water quality concentrations for runoff sampled at Lake Harrison inflow and outflow. Since runoff volumes were roughly equivalent, a comparison of relative loadings is redundant to the comparison of mean concentrations. Greater values for ortho-P, NH_3, NO_2 and NO_3 indicate the outflow was nutrient enriched as a result of one or a combination of two sources:

(1) Unmeasured runoff from the fertilized area adjacent to the lakes and/or direct precipitation on the lakes,

(2) The quality of water held in the lakes prior to the storm event. (Water impounded in the lake prior to the storm event approximated the runoff volume.)

Lake Harrison served as an equalization basin minimizing the difference between maximum and average parameter concentrations. A prominent flush corresponding to the first peak of the Lake B hydrograph was evident for most parameters at the inflow. For example, nitrate concentration at the flush, maximum value, was an order of magnitude greater than average concentration. This flush was not observed at Lake A and average concentrations approximated maximum concentrations.

Sediment removal-- Superimposed on the lake hydrographs of Figure 33 are the TSS pollutographs. The reduction of solids by sedimentation is a significant lake function desirable in stormwater management. The high TSS concentration of 2660 mg/l at inflow was reduced to 356 mg/l at outflow. Detention in Lake Harrison reduced the stormwater sediment load from 160 tons (145 t) to 31 tons (28 t), an 80% reduction in solids, storing 129 tons (117 t). This mass reduced the volume of the 110 acre (13.56 ha-m) lake by less than 0.1% if 80 lb/ft^3 (1282.3 kg/m^3) is assumed. Erosion from Lake B watershed was effectively prevented from entering Panther Branch by the lake system.

Table 26 shows the reduction in stormwater sediment load by Lake Harrison for all storms monitored. All but one storm event recorded over 80% solids removal. Complete removal, 100%, is a

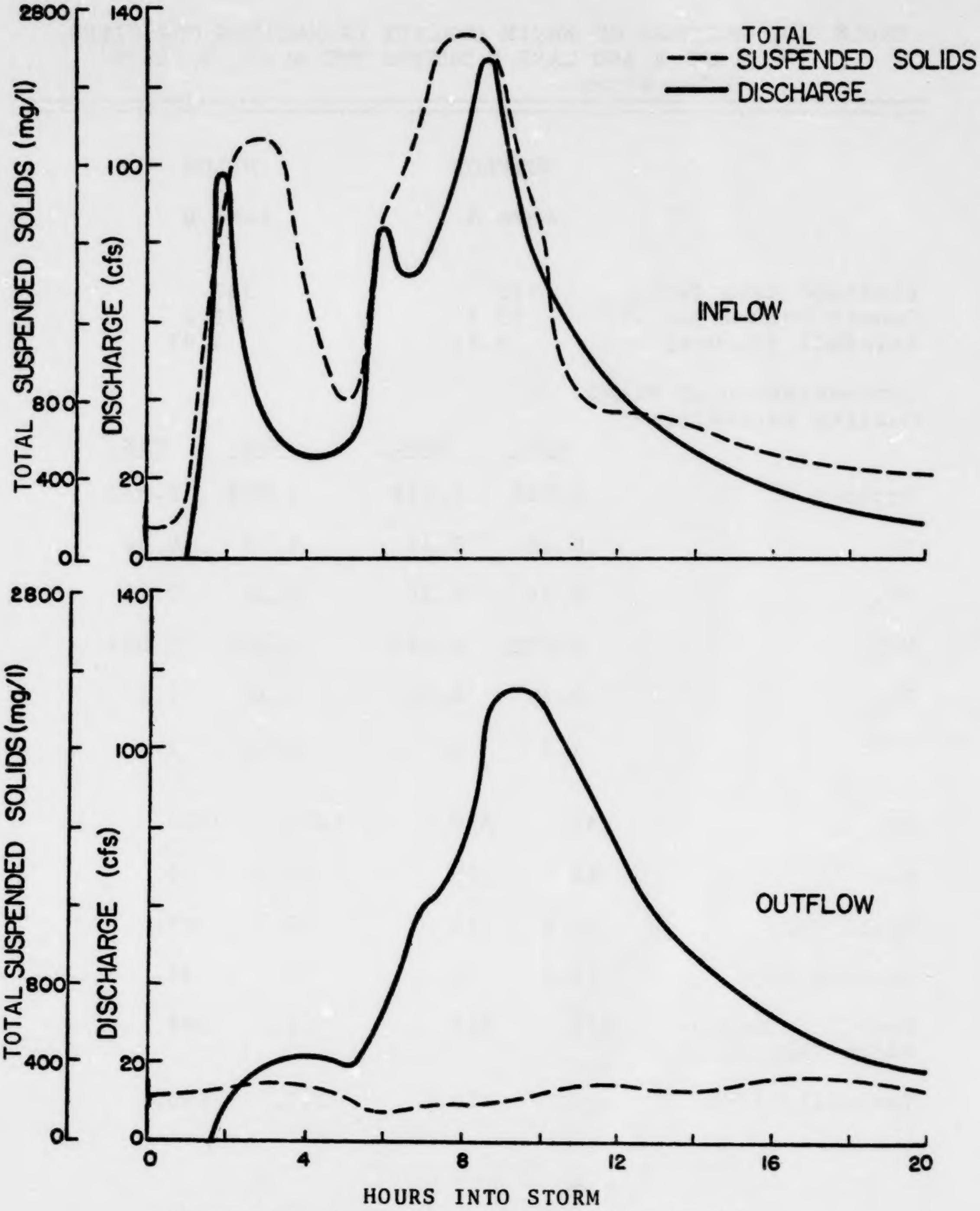


Figure 33. Reduction of TSS through The Woodlands lake system.

1 cfs = .028 m^3/sec

TABLE 25. SUMMARY OF WATER QUALITY PARAMETERS FOR SITES LAKE A AND LAKE B DURING THE APRIL 8, 1975 STORM EVENT

	OUTFLOW		INFLOW	
	Lake A		Lake B	
Drainage Area (acres)	483		337	
Runoff Volume (ac-ft)	93.4		93.2	
Rainfall (inches)	3.97		3.97	
Concentration of Water Quality Parameters:*				
	Avg.	Max.	Avg.	Max.
Ortho-P	0.015	0.048	0.005	0.013
TP	0.10	0.19	0.11	0.36
NH_3	0.16	0.26	0.11	0.15
NO_2	0.032	0.046	0.009	0.054
NO_3	0.28	0.32	0.15	2.1
TKN	1.3	2.	1.86	3.1
TSS	245.	356.	1273.	2660.
SOC	13.6	19.	16.2	22.
Total COD	41.8	45	63.7	87.
Soluble COD	26.4	31.	32.	45.
Specific Conductance (micromhos)	130.	215.	85.	304.
Turbidity (JTU)	160.	210.	375.	900.

1 ac = .405 ha

1 ac ft = .123 ha-m

1 in = 2.54 cm

*all concentrations in mg/l except where indicated result of total stormwater storage by Lake Harrison and does not preclude discharge at a later time.

TABLE 26. STORMWATER SEDIMENT REMOVAL AT LAKE HARRISON

	TSS Load During Storm Event		
Storm #	lbs[1] Input (Lake B)	lb Discharged (Lake A)	% Load Reduction
8	104	Flow stored within lake	100%
9	13800	991	93%
10	322000	61900	80%
13	6700	Flow stored	100%
14	11530[2]	1850	84%
15 & 16	4840	3270	32%

[1] 1 lb = .453 6 kg

[2] Estimated value (Lake B gage inoperative) calculated using estimated 10.1 ac-ft (1.24 ha-m) inflow times sample average concentration, 421 mg/l.

Disinfection--

The FC standard adopted by the State of Texas for contact recreation is 200/100 ml ($\log_{10} = 2.3$) (53). For noncontact recreation the figures are one order of magnitude higher, i.e., 2,000/100 ml ($\log_{10} = 3.3$). Sixteen of 27 storms, considering all stations, exceeded the noncontact recreation standard. All the Westbury storm events exceeded the standard. Contact recreation standards were met only for Lake A stormwater sampled on 3/4/75 and 3/12/75.

Dry weather flow in Panther Branch met the contact recreational standard at site P-10 but not at site P-30. The mean FC value for P-10 low-flow data was 2.13 ($\log_{10}$ basis) indicating that, on the average, the criteria for contact recreation is satisfied. However, the value for stream water at P-30 was 2.38 and therefore unacceptable.

Disinfection of stormwater is feasible, and it is generally agreed that large dosages will be required to achieve adequate reduction in indicator and pathogen densities. Chlorine or chlorine dioxide has been reported to be the most effective disinfectant, and in many cases the least expensive (54, 55, 56). Davis et al. (57, 58) discussed current disinfection research and practices along with encountered problems which occur in combined sewer disinfection and stormwater disinfection.

Samples were obtained from different locations during storm events to determine disinfectant demand and effectiveness of ozone and chlorine. Chlorine demand of Lake A stormwaters on 3/13/75 and 4/7/75 was 10 mg/l, and the ozone demand was in excess of 32 mg/l. These elevated demands were partially due to suspended solids and oxidizable materials competing for the disinfectant. As a result, stormwater disinfection will be costly.

Chlorine and ozone toxicity--Water quality standards often state that the final concentration of any waste in a receiving water should not exceed 1/10 of the 96 hour LC_{50} value (59). To assume that 1/10 of even a true 96 hour LC_{50} would not have severe physiological effects and truly impair natural propagation of all species is unrealistic. Tsai (60) reported that species shifts occurred following the introduction of chlorine into a Maryland river. Also, Arthur and Eaton (61) show that the reproduction of fathead minnows is drastically affected by exposure to sublethal concentrations of chlorine. This evidence suggests that sublethal concentration of chlorine is capable of producing significant physiological impairment.

The approach taken herein was to establish a chlorine standard based on physiological responses of the test animal. The effect of chlorine and ozone exposure on the physiological function of Ictalurus punctatus (the channel catfish) has been examined. The physiological parameters evaluated were heart rate, blood pressure, sodium uptake, ion excretion, and glomerular filtration. In addition, typical LC_{50} bioassay tests were completed for comparative purposes. Significant results are presented in the following paragraphs.

Survival-mortality characteristics--The survival-mortality characteristics of fingerling channel catfish to chlorine were examined and results are shown in Figure 34. A flow through bioassay compared to a static bioassay results in a lower 96 hour LC_{50}. The LC_{50} concentrations of 0.07 mg/l for the flow through bioassay and 0.45 mg/l for the static bioassay were read directly from the figure. A flow through or continuous flow bioassay is a more accurate measurement for 96 hour LC_{50} of a highly reacting toxicant like chlorine (62). The chlorine concentrations in Figure 34 are based on the measured amounts of total residual chlorine added to the inflow and do not represent concentrations during tests with fish. Thus the chlorine concentrations shown

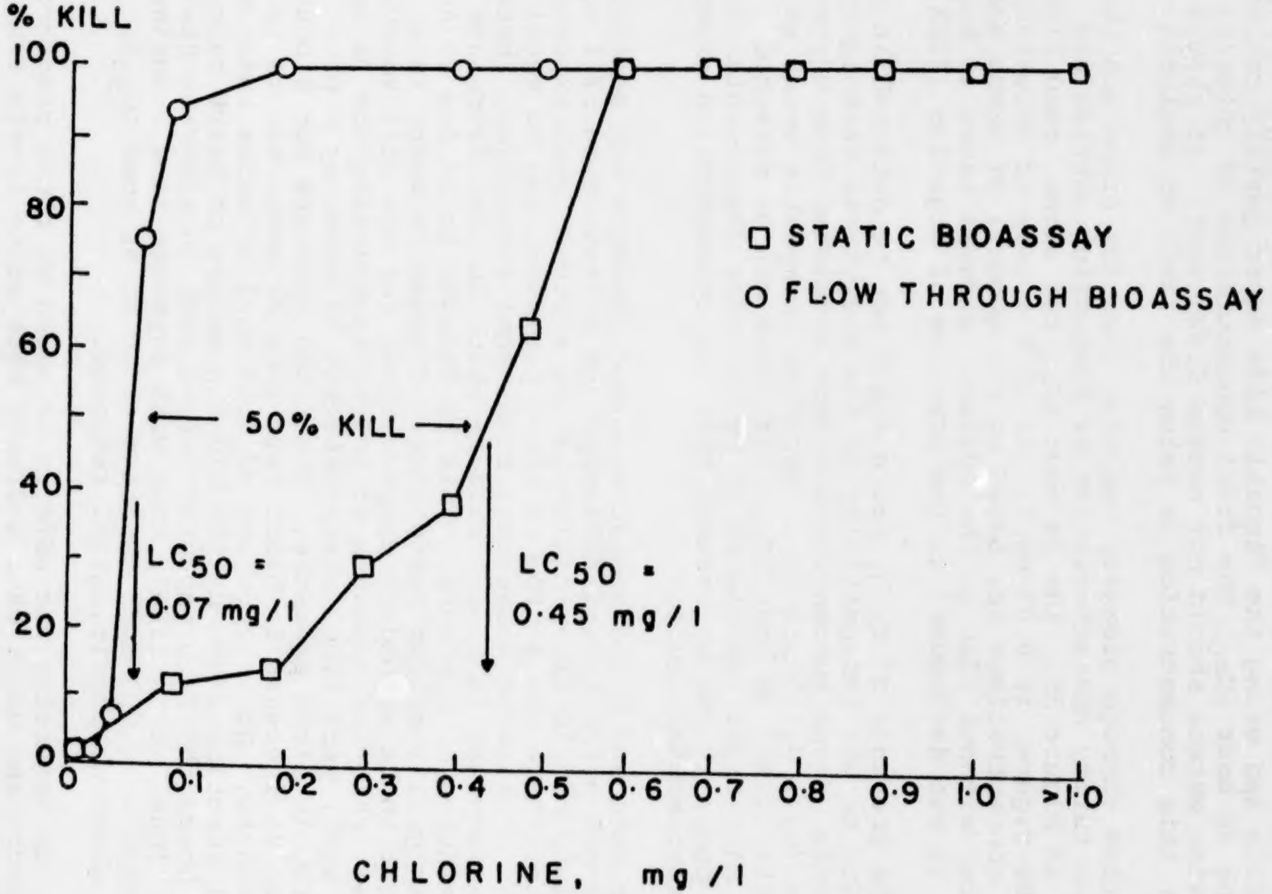


Figure 34. A comparison of survival-mortality characteristics of fingerling catfish to chlorine exposure in a static bioassay and in a flow through bioassay.

are levels that would be representative at treatment outfalls. Samples taken from receiving waters should show chlorine concentrations significantly lower. Based on a 96 hour LC_{50} of 0.07 mg/l chlorine and using the "Aquatic Life Water Quality Criteria" of 1/10 the 96 hour LC_{50}, the final concentration of chlorine in the receiving waters should not exceed 0.007 mg/l. It should be noted that this concentration is below the limit of analysis.

The flow through bioassay was also used for ozone and the survival-mortality characteristics of fingerling catfish are presented in Figure 35. The 96 hour LC_{50} for ozone, read directly from the figure, is 0.03 mg/l. As in the case of chlorine, the ozone concentrations are based on the amounts of ozone added to the water without fish in the system. Because ozone is highly reactive, it was decomposed in the presence of organics (fish).

In the presence of fish, ozone could not be detected in the bioassay due to the insensitivity of the analytical technique. At low levels, ozone concentrations were estimated from oxygen flow rates (mg/l O_3: l/min O_2). Based on acceptable water quality criteria (1/10, 96 hour LC_{50}), if ozone can be detected either by analytical techniques or by its odor (detectable odor 0.02-0.05 ppm), it can be assumed that its concentration exceeds a safe environmental limit.

Heart rate and blood pressure--Blood pressure was continuously recorded prior to and following the introduction of 1 mg/l chlorine into the 10 liter recirculating system. Upon exposure to chlorine, there was a drop in blood pressure, due to vagal inhibition. Following escapement from vagal inhibition, there was a mean increase in blood pressure which in turn decreased after 15 minutes of exposure. This is thought to be due to an increase in gill vascular resistance. Changes in heart rate were thought to be secondary compensations for the gill vascular resistance. Chlorine exposure at levels approaching the 96 hour LC_{50} (0.7 mg/l) were immediately detected as shown by a pronounced drop in blood pressure. Continued exposure for 5 hours resulted in an increase in heart rate from 22 beats/minute to 45 beats/minute. At an exposure of 0.03 mg/l chlorine there was no initial reaction shown by the blood pressure or heart rate. After two hours the fish appeared normal with no apparent disfunction. Thus, it is likely that with exposure to a chlorine concentration of 0.007 mg/l chlorine (1/10 of 96 hour LC_{50}), fish will shown no physiological response.

Tests to determine the effects of ozone on blood pressure, pulse pressure and heart rate indicate that ozone levels from 0.1 to 0.5 mg/l for 10 hours had no apparent effect.

Gill sodium transport--The influence of chlorine exposure on the uptake of ^{22}Na by gills of fish is shown in Figure 36. The disappearance of ^{22}Na from aqueous phase (ordinate axis in Figure

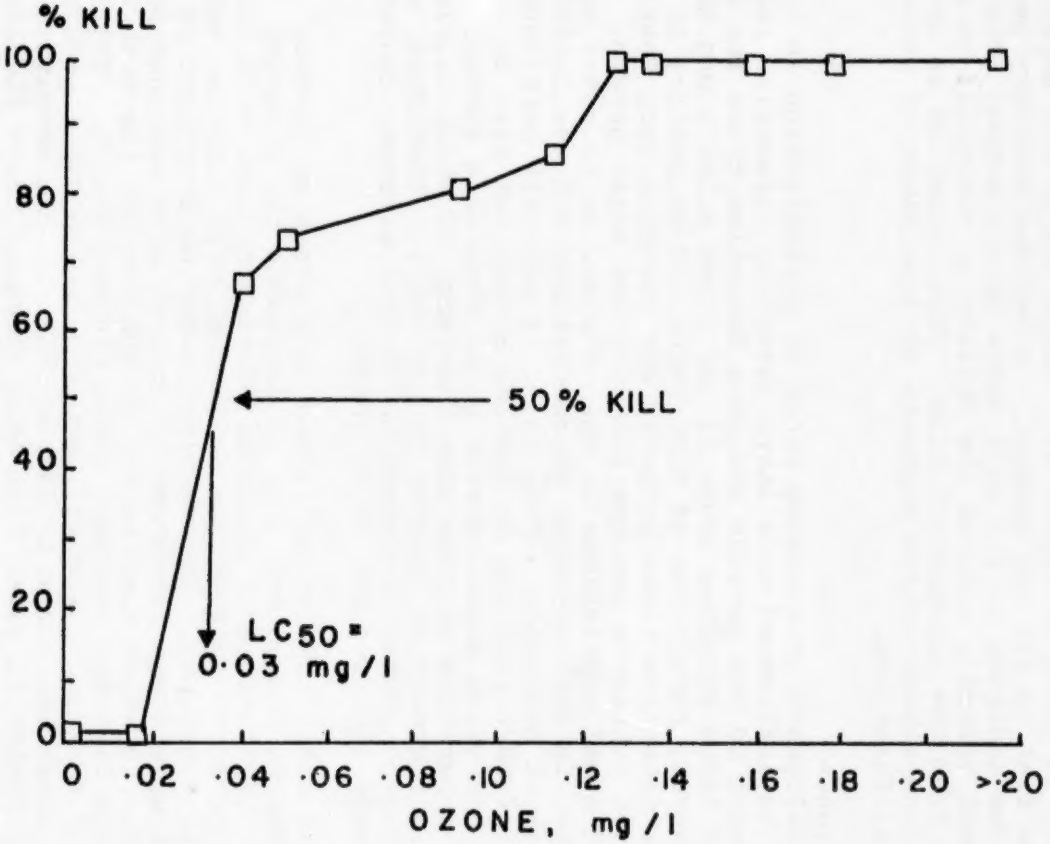


Figure 35. Survival-mortality characteristics of fingerling catfish to ozone exposure in a flow through bioassay.

36) is a measure of the removal of ^{22}Na by the gills of the fish. The addition of 0.1 mg/l of chlorine at the start of the experiment markedly reduced the ability of the gills to remove sodium from aqueous solution. This reduction in uptake rate following chlorine exposure suggests an impairment of normal physiological function in the sodium transport system.

The influence of ozone exposure on the uptake of ^{22}Na by the gills of fish is shown in Figure 37. Phase one of the experiment utilized the fish as its own control. A one day recovery period followed. The addition of 0.1 mg/l ozone in the second phase of the experiment markedly reduced the ability of the gills to remove sodium from the aqueous solution. This reduction in uptake following ozone exposure also suggests an impairment of normal physiological functions.

Eutrophication--

The development of standing crops of phytoplankton in Panther Branch is influenced to a large extent by streamflow rates. High flow rates do not provide adequate detention times for development of large standing crops at any given point along the stream. However, reductions of flow rates and/or pooling in the stream allow detention times suitable for standing crop development, provided nutrients are not limiting for algal growth. Development of algal populations in this stream, as in other aquatic ecosystems, is influenced by concentrations and availability of various algal nutrients. This point is not only pertinent to development of phytoplankton in Panther Branch but also to aquatic systems which might receive water from this stream. Thus, it is imperative to have some knowledge of which nutrients stimulate algal growth in Panther Branch water. Therefore, algal bioassays were conducted to determine whether nitrogen and/or phosphorus were limiting for algal growth.

Low-flow water samples collected from sites on Panther Branch and Spring Creek were used to determine the limiting nutrient for algal growth. Aliquots of stream water were inoculated with the algae Selanastrum and spiked with nitrogen and/or phosphorus as nutrients. The results presented in Figure 38 indicate algal growth was increased by additions of both nitrogen and phosphorus to water samples and phosphorus was the most important single limiting nutrient along Panther Branch. The introduction of treated sewage effluent and agricultural runoff into Spring Creek was probably responsible for the comparatively larger algal yields in water from this stream. These findings are in contrast to results derived from bioassays of stormwater.

Algal bioassays were also conducted with water collected from Panther Branch at various time intervals during the course of storm events. The stormwater runoff collected below the major area of construction in The Woodlands (site P-30) seemed to fluctuate in its ability to support the growth of algae (Figure

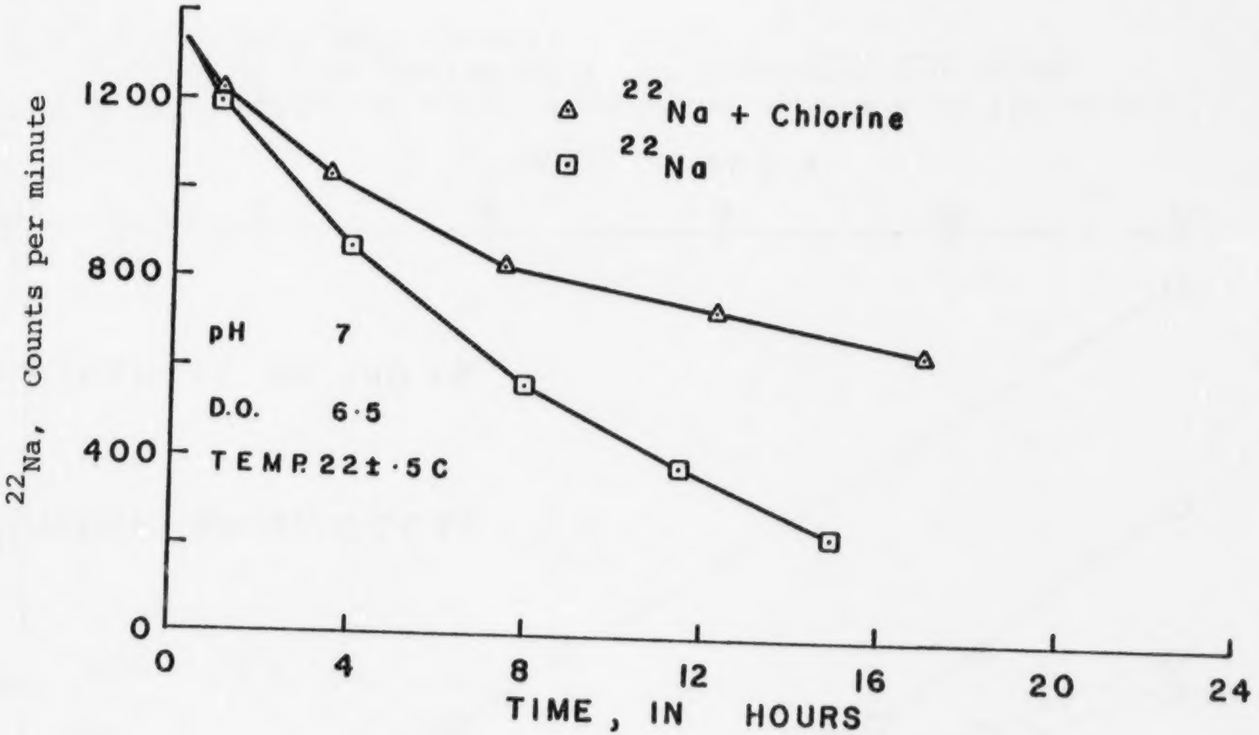


Figure 36. Effect of Short Term Chlorine Exposure on the Uptake of ^{22}Na by the Gills of Ictalurus punctatus (0.1 mg/l chlorine).

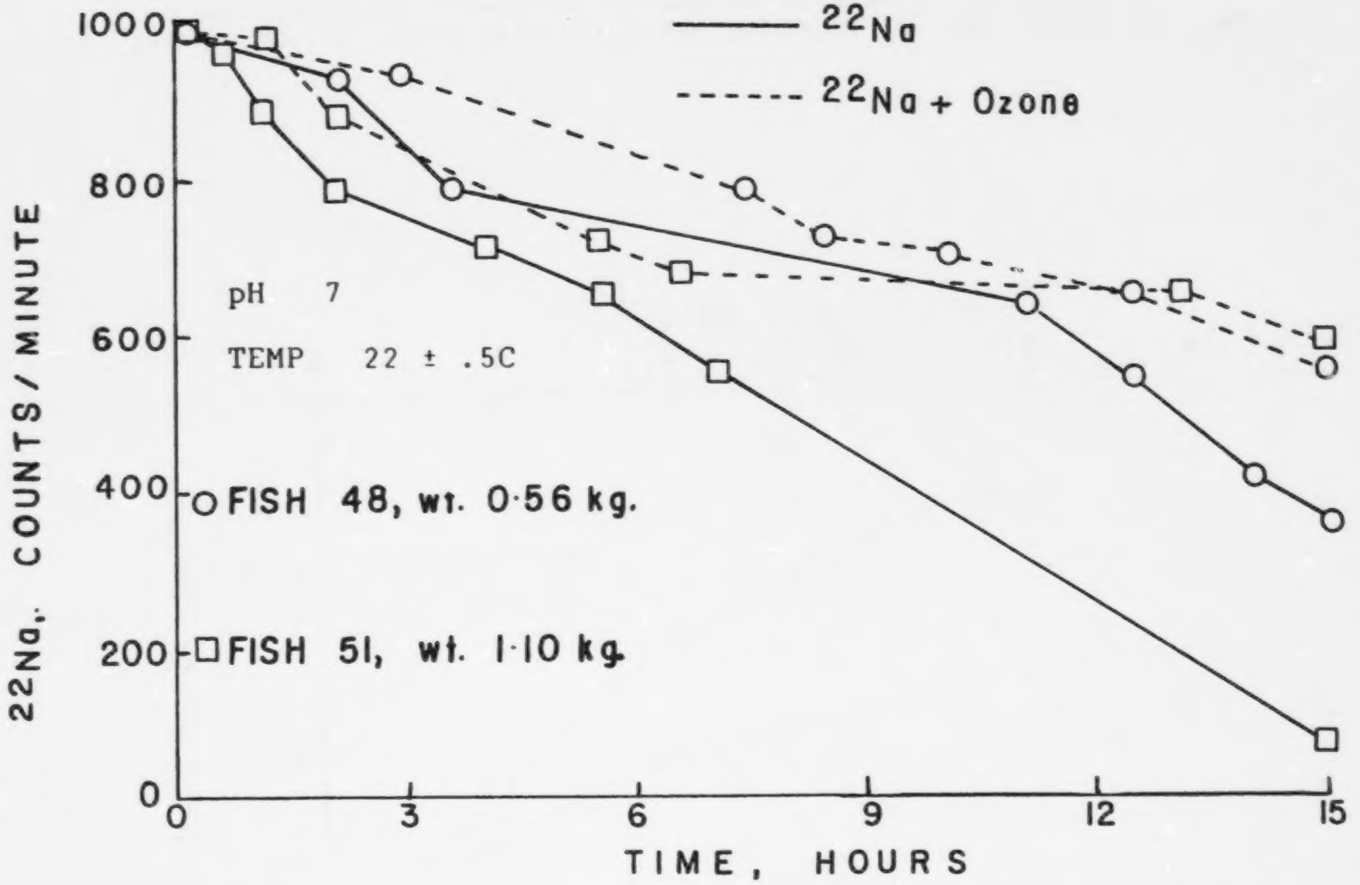


Figure 37. Effect of short term ozone exposure on the uptake of ^{22}Na by the gills of Ictalurus punctatus (0.1 mg/l ozone).

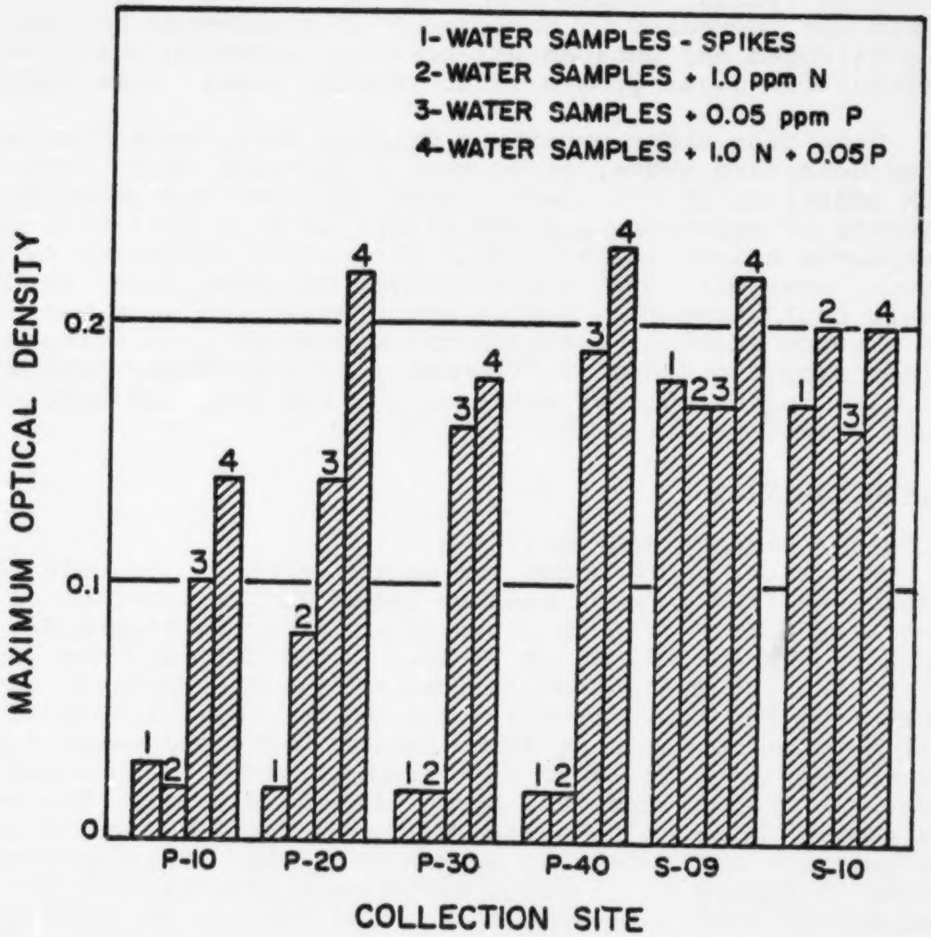


Figure 38. Optical densities of Selenastrum capricornutum after incubation in water from Panther Branch and Spring Creek (May, 1974).

39). Test samples collected early in runoff at P-30 demonstrated the greatest growth in both control and spiked aliquots. These samples corresponded to high nutrient stormwaters from the fertilized areas of The Woodlands, not present at site P-10. As runoff at P-30 progressed there was a decrease in algal cell yields to similar levels observed for P-10 test samples. Algal growth was increased by enrichment of stormwater samples with both nitrogen and phosphorus; however, nitrogen was consistently limiting for algal growth in stormwater runoff from The Woodlands.

Data from storm events at Hunting Bayou were similar to those described above, indicating a stimulation of algal growth with additions of nitrogen or both nitrogen and phosphorus to the majority of water samples and slight or no stimulation with only phosphorus spikes (Figure 40). The marked reduction in algal growth, even with combined nitrogen and phosphorus, in the 4:30 sample could have been due to the presence of some toxic agent or the absence of some essential trace element. Additional data obtained from bioassays of stromwater from Westbury Square (Figure 41) also indicated that nitrogen was the limiting nutrient for algal growth in stormwater runoff.

Porous Pavement

Rainwater Storage and Quality--

The water depth under the porous pavement in both the sand subbase and the general storage layer during a period of rainfall from 3/6/76 to 3/8/76 is shown graphically in Figure 42. The depth of the sand layer is 33 in. (84 cm), and the layer shows saturation resulting from failure of the French drain to remove water from the lower levels. The gravel layer responded to rainfall by storing water as shown by the increased water depth in the gravel layer followed by a gradual decrease in depth as the water was drained from the top of the sand layer. The height of the stored water and the time to reach the peak height depend on the quantity and intensity of the rainfall. This is best illustrated in Figure 42 in which seven separate rainfall events occurred over a 60 hour time span. The first three events, totaling 1116 ft^3 (31.6 m^3), were spread over approximately five hours and produced an even response with a peak of approximately six in. The subsequent event at 21 hours involved only 283 ft^3 (8 m^3) of rainfall and increase in stored water height of 1.8 in. (4.6 cm). For the two major storm events occurring at 28 and 48 hours, the water level had not drained sufficiently and the increase in stored water height exceeded the measuring probe length. The time required for the majority of stored water to drain away was approximately 10 hours.

The quality of the water in runoff from the standard pavement and in the gravel and sand layers beneath the porous pavement was monitored during six storm events. As expected, there was a general flushing effect for the runoff water with initially

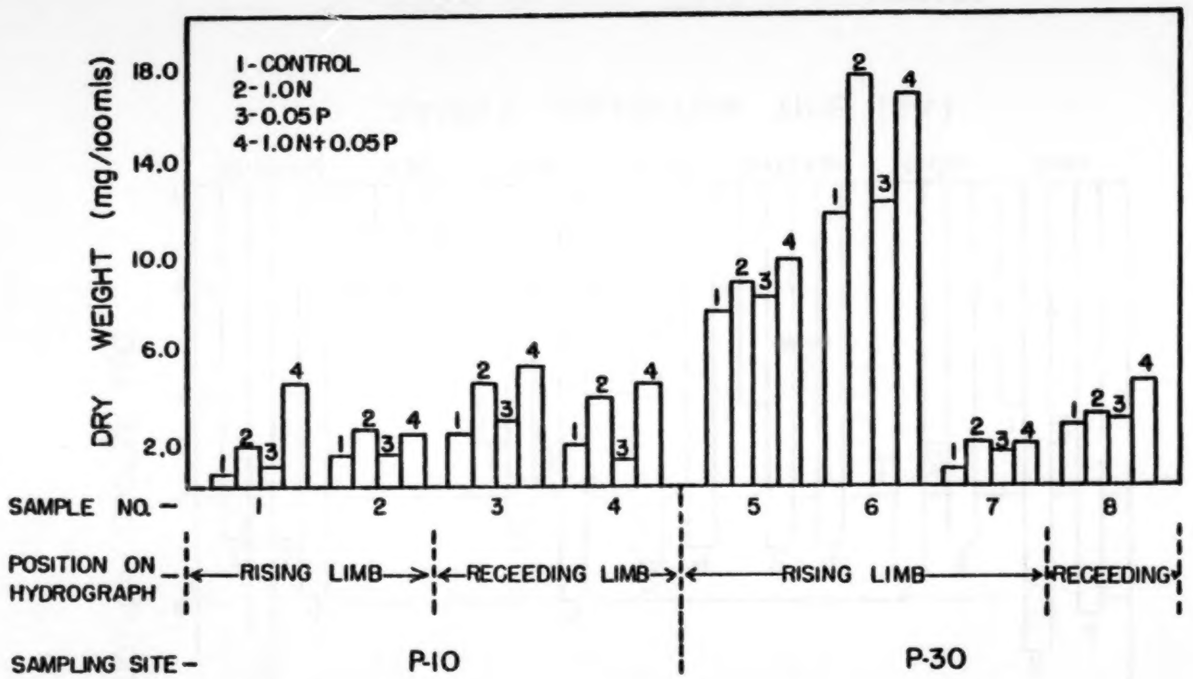


Figure 39. Growth of Selenastrum in stormwater runoff in relation to hydrograph position at P-30 (April, 1975).

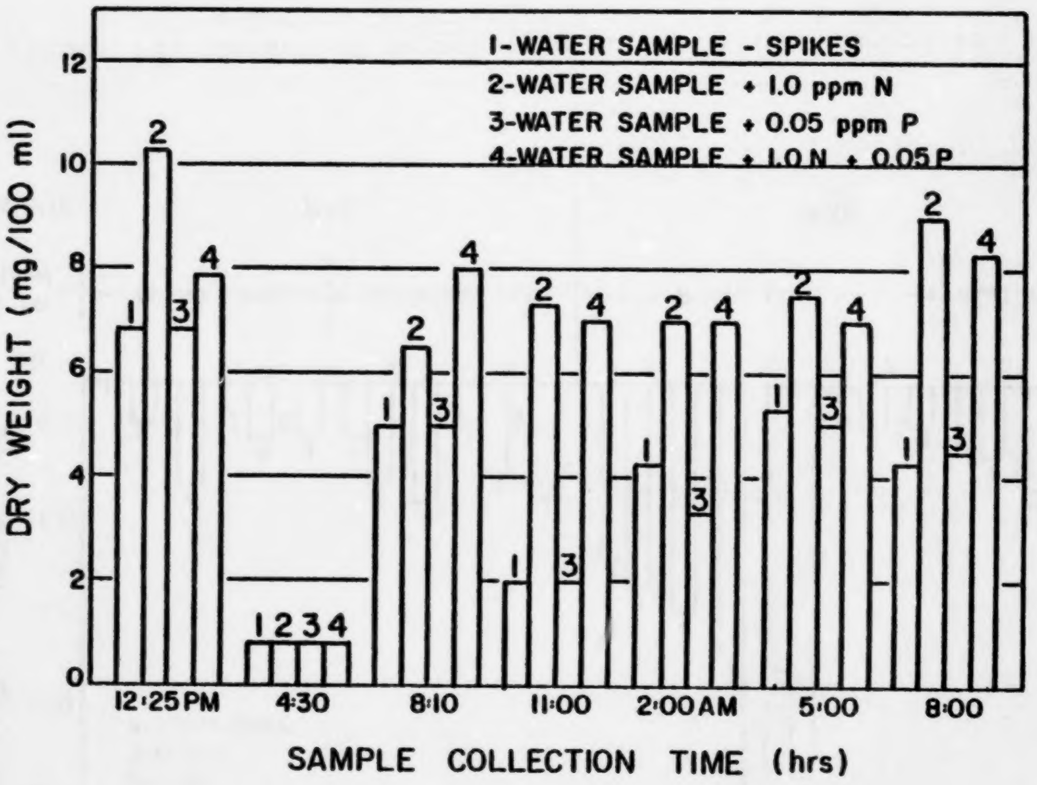


Figure 40. Growth of *Selenastrum* in stormwater runoff from Hunting Bayou (March 26, 1974).

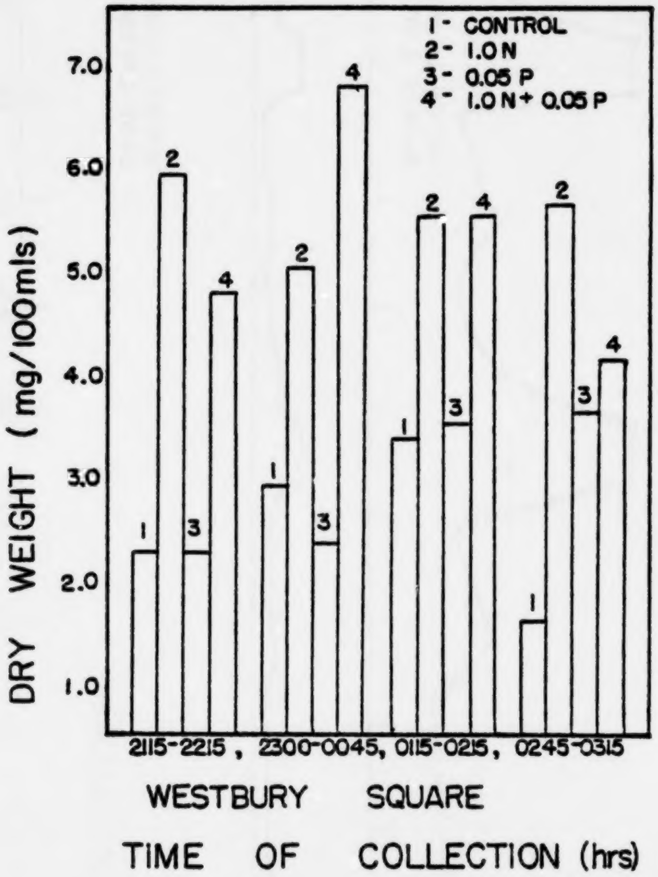


Figure 41. Growth of *Selenastrum* in stormwater runoff from Westbury Square (May 8, 1975).

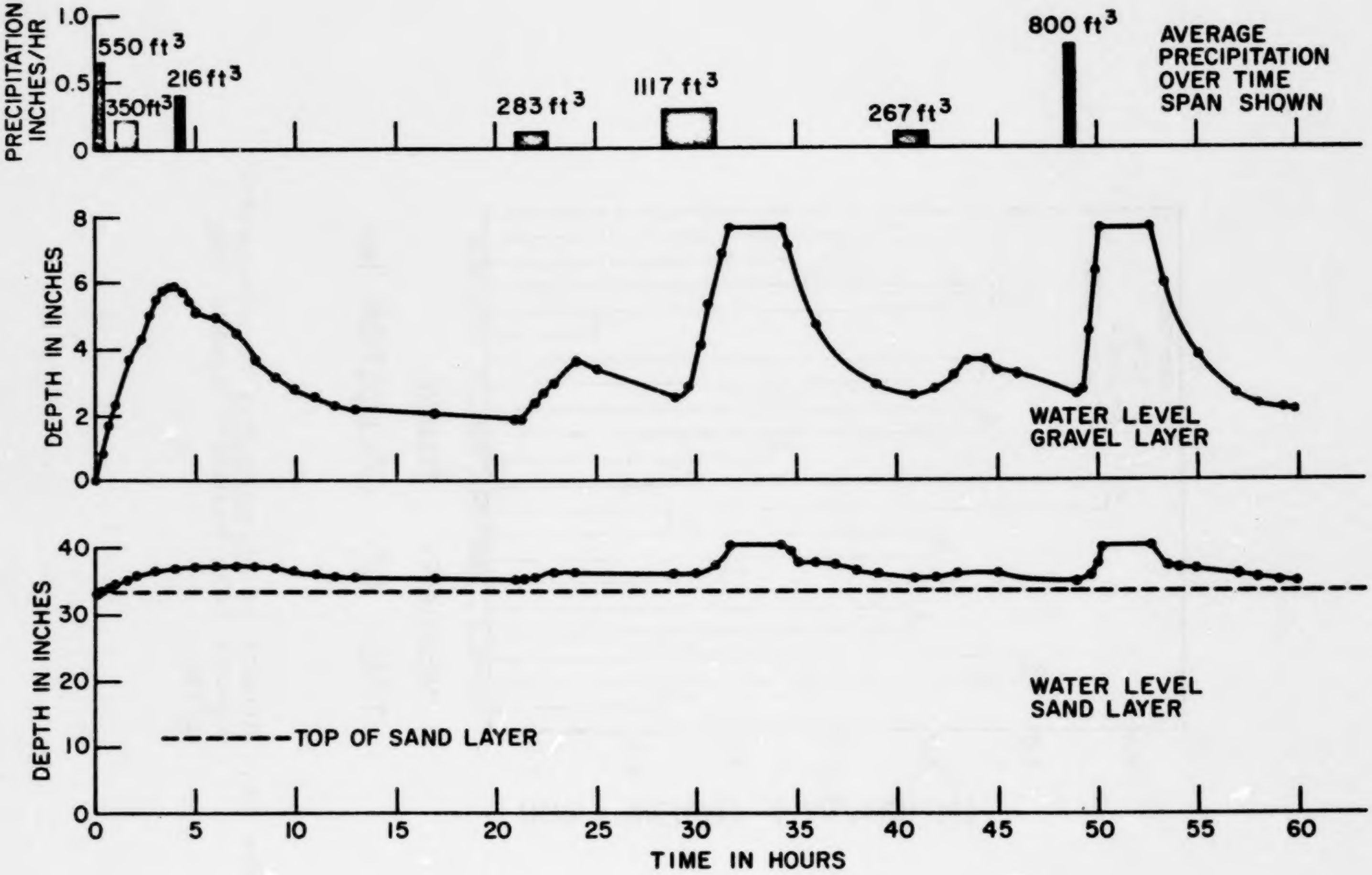


Figure 42. Water depth and rainfall for storm event of 3/6/76 to 3/8/76.

1 ft^3 = .028 m^3

1 in = 2.54 cm

high concentrations of contaminants which then rapidly decreased. The rapidity if change is not evident in the water underlying the porous lot. Table 28 presents a summary of stormwater quality data collected during a 0.44 in. (1.12 cm) rainfall on 2/20/76, which is exemplary of the monitroing effort. SOC and soluble COD are generally lower in the water under the porous lot than in the runoff from the standard pavement, but the reverse is true for conductivity, TKN, and NH_3. This is apparently a result of the failure of the French drain to completely drain the sand layer beneath the porous lot. The lower COD and TOC values, together with the high Kjeldahl and ammonia nitrogen, indicate than an anaerobic digestion process is occurring in the standing water. Lead values are generally lower in the water under the porous lot and, in most cases, would be acceptable in aquifers. The few cases where high lead values were found in the underlying layers do indicate that before porous paving is used for recharge of aquifers by percolation information must be obtained on the ability of soils to remove lead from leachates.

Wet Skid Resistance--

A modification of the locked wheel test was used to determine the coefficient of sliding friction between a standard passenger vehicle tire (size 6.50 x 13) and the test pavements, both wet and dry. In the case of the porous pavement, tests were made on a section of the original paving and on a repaired section. Test results for three series are shown in Table 27.

TABLE 27. COEFFICIENT OF FRICTION

Test Date	Paving and Condition	Reaction Force (lbs)	Coefficient of Sliding Friction (μ)
12-3-75	Old porous - dry	43.2	.605
	Old porous - wet	60.8	.851
	New porous - dry	47.2	.661
	New porous - wet	52.8	.739
	Standard - dry	52.0	.728
	Standard - wet	42.4	.594
2-5-76	Old porous - dry	58.4	.818
	Old porous - wet	68.0	.952
	New porous - dry	59.2	.829
	New porous - wet	64.0	.896
	Standard - dry	71.2	.997
	Standard - wet	57.6	.806
4-23-76	Old porous - dry	52.5	.735
	Old porous - wet	60.0	.840
	New porous - dry	57.0	.798
	New porous - wet	60.0	.840
	Standard - dry	55.5	.777
	Standard - wet	51.0	.714

1 lb_f = .138 nt

TABLE 28. SUMMARY OF STORMWATER QUALITY FOR POROUS PAVEMENT STORM ON 2/20/76

	Porous Pavement				Conventional Pavement Runoff	
	Gravel Layer		Sand Layer			
Constituent[1]	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
pH	8.1	0.2	8.0	.04	7.8	.23
Sp. Cond.	457	14.	542	12.	108	54.
Soluble COD	35.	5.8	35.	3.7	60.	35.
SOC	15.	4.4	13.	2.8	30.	16.
TKN	2.5	.42	2.7	.46	1.2	.42
NH_3	1.5	.41	1.33	.28	.15	.09
NO_3	.12	.14	.03	.01	.36	.17
NO_2	.014	.017	.004	.002	.013	.009
TP	.10	.02	.50	.08	.11	.04
ortho P	.06	.02	.48	.06	.06	.02
Pb	.05	.03	.03	.01	.31	.43
Zn	.18	.39	.27	.18	.34	.21
	n = 11		n = 11		n = 10	

[1] all measurements in mg/l except pH in pH units and specific conductance in μmhos/cm^3

[2] $\bar{x}$ = mean

s = standard deviation

n = number of samples

In most cases the standard, dense paving exhibited dry skid resistance better than or equal to the two porous pavements. The reverse was true when wet paving was tested with the porous pavements being clearly superior. For standard pavement, the coefficient of friction under wet conditions was, as expected, lower than under dry conditions. However, a consistent behavior pattern for the porous pavements, for which there is currently no verified explanation, is the increase of the coefficient of friction on wet pavement over that on the dry pavement. One possible explanation is that in the case of the wetted pavement surface dust layers have been washed through the pavement and the rougher surface then comes into full play.

Noise Levels

Traffic noise levels (Table 29) were determined using two different vehicles, both equipped with standard steel belted radial tires. Measurements were made early in the morning to avoid external noise interference.

TABLE 29. NOISE LEVELS 1 mi = 1.6 km

Paving	Vehicle	Speed (mph)	Noise Level[1] (dB)
Old porous	1	15	A62
New porous	1	15	A57
Standard	1	15	A64
Old porous	2	15	B68
New porous	2	15	B68
Standard	2	15	B71
Old porous	2	20	B69
New porous	2	20	B69
Standard	2	20	B73

The porous pavings are less noisy than standard paving.

[1] A scale consistent with human ear. B scale filters to accentuate lower frequency sound.

Porosity

In situ porosity was determined on the porous pavements by grouting in place a 6 in. diameter tube having two scribed lines 5 in. apart. Water was placed in the tube and the time required for the water level to pass the marks was measured. Results are calculated in in./sec of water transmission. The section of new porous pavement gave the best water transmission than that in the original pavement. Water transmission rates in the new pavement were normally 0.55 in./sec (1.4 cm/sec) while the original sections exhibited a normal porosity of 0.38 in./sec (0.96 cm/sec). Sections of original paving were found to be clogged. These sections were primarily near the curb or near the curbing at the upper side of the lot opposite the curb. The clogging near the curb resulted from mud and dirt from the wheels of contractors' trucks, while the clogging of the upper lot was chiefly from cement dust from curb construction and find sand and silt washed from the grass plot before the grass gave adequate cover. The partially clogged or completely clogged areas were marked for studies of cleanability.

Cleaning and Maintenance

It was recognized early in the program that maintenance and cleaning of porous pavement to prevent or alleviate clogging would be a factor in the application of such pavements. Sections of the porous pavement which were clogged were cleaned by various methods. No method was satisfactory on fully clogged pavement and only a superficially clogged section, showing a water penetration of 0.38 in/sec (0.96 cm/sec), could be restored to normal operation. The best method for cleaning was brush and vacuum sweeping followed by high pressure water washing of the pavement. Vacuum cleaning alone, once the pavement is clogged, was found to have no effect. The oils in the asphalt bind dirt and only abrading and washing techniques are effective in removal. By removing fractional thicknesses of paving, it was observed the clogging to a depth of 0.5 in (1.3 cm) was sufficient to prevent water penetration.

Damage to pavement porosity results chiefly from abuse during the early life of the paving. Normally, paving is carried out while heavy construction and earth moving is continuing in the area and is subjected to mud and dirt from contractor vehicles for up to several months. Continual passage of these vehicles serves to compact dirt into the pores. Porosity can be retained only if the paving is cleaned daily by sweeping and high pressure water washing.

Once a large area of porous pavement is fully clogged it cannot be adequately cleaned and the paving must be removed to a depth where the clogging is not evident and new porous paving filled in. In extreme cases, the affected area of the porous topping must be removed and new topping put down.

Both the standard and porous pavements showed signs of the effect of heavy vehicle passage and of power steering damage. Heavy vehicles tended to leave tire depressions in either lot on hot days while power steering damage was evidenced by small circular depressions in the lot surface. The latter damage occurs when wheels are turned when a vehicle is not in motion. The use of a lower penetration asphalt for pavements should offset the damage to paving in warm climates.

Pavement Deflection

Pavement deflections in porous and standard surface lots were measured on four different occasions. Measurements were made of pavement acceleration and time duration of acceleration as it deflected on passage of the test vehicle. Test results indicate there are no real differences in the magnitude of the deflections, but the time duration of the deflection was always longer for the porous pavement than for the standard pavement with correspondingly lower "g" levels. This long response may be responsible for the lessened tire noise observed in the sound level tests.

Pavement Survey

Visits were made to four locations where porous paving is in use. The locations at the University of Delaware, Newark, Delaware, Bryn Mawr Hospital, Bryn Mawr, Pennsylvania, and at The Marine Sciences Consortium, Lewes, Delaware were in good condition with little or no indication of pavement clogging. The paving at a Travelodge in Tampa, Florida showed considerable clogging from sand and silt caused by passage of trucks on the nearby road and inadequate curbing to prevent surrounding soil from washing onto the lot. Degradation of the surface was evident in the form of patches of loose stone and gravel.

It is evident from the damage at the Tampa lot and in the lot at The Woodlands that a lower penetration asphalt should be used in the topping, especially in warm areas. Again, it is felt that clogging can be minimized by proper use of curbing to prevent surrounding soil from washing onto the lot surface. Recent installation of porous paving at The Franklin Institute parking lot in Philadelphia, Pennsylvania has further pointed up the need for close control of contractor vehicles on a newly installed lot. It was necessary to sweep away caked mud from vehicle wheels and then wash the affected area with high pressure water.

Traffic Paint Visibility

Two colors of traffic paint, white and yellow, with and without addition of glass beads, were applied to the pavements. They were photographed under equal incident lighting intensities at night under wet and dry conditions and the reflected light intensity was determined from image densities on the negatives. The white marking paint showed a slight superiority in visibility over the yellow whether or not glass beads were added. No real difference in the reflected light intensity from either pavement, wet or dry, was evident. The test, however, did not evaluate glare from oncoming vehicle lights which may obscure reflected light from paint on a wet, non-porous pavement.

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